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073 4599 6001

4. Title of the invention

OPTICAL PHASE DETECTOR

5. Name of your agent (if you have one)

Bowdery, Anthony Oliver

"Address for service" in the United Kingdom to which all correspondence should be sent (including the postcode)

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D/IPR Formalities Section (DERA)
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Optical phase detector

The invention relates to an optical phase detector for measuring the phase difference between two input signals. The invention also relates to applications of an optical phase detector, including use in an optical frequency discriminator and a laser stabilisation apparatus.

Conventionally, phase difference may be measured optically by interfering two beams to form an interference fringe pattern and measuring the fringe pattern as it moves across a camera face due to a change in the relative phase. A disadvantage of this type of measurement is that it relies on the counting of fringes and interpolation between fringes to measure phase or position accurately. This process can be relatively slow and not especially accurate. Such detectors may be used in displacement measurement schemes, such as in laser metrology, to measure position accurately i.e. to a fraction of an optical wavelength.

Optical techniques have previously been used for the generation of microwave radiation, by mixing two stable lasers, and for phased array antenna beam-forming, in which simple optical systems are used to perform a complicated microwave function. A known technique for the generation of stabilised microwave radiation has been achieved by incorporating a fibre optic delay line in an rf, microwave or millimetre wave (mm-wave) frequency discriminator circuit. This enables the difference in frequency of two stable laser inputs to be controlled accurately and therefore the rf, microwave or mm-wave output can be stabilised (UK patent application 9523518.0). In this system the frequencies of the lasers can drift but the difference in frequency between them remains constant. It is an object of the system to provide an apparatus for providing stable radiation at rf frequencies.

In many applications high spectral purity (i.e. stable) laser radiation is required. These applications, include photochemistry, luminescence excitation spectroscopy, absorption and Raman spectroscopy, fibre optic communications, sensors, laser radar, laser air speed indicators and laser vibrometry. However, lasers of well defined frequency (or wavelength) and high spectral purity (e.g. narrow linewidth) tend to be expensive and complex. High spectral purity is attainable with certain gas lasers, but there is a need for solid state lasers of similar performance. Solid state lasers include laser diodes and diode pumped YAG lasers. The most widely used laser device is the laser diode. Although these devices are relatively cheap, devices of this kind have a particularly poor spectral stability, especially in the case of Fabry-Perot etalon designs which often support several modes simultaneously.

For many applications, it is useful to overcome the problem of poor spectral quality and to be able to stabilise the frequency output of a single laser. Furthermore, for some applications, extremely pure laser radiation is required.

The stabilisation of a laser output with an external component has previously been reported [*FM noise reduction and sub kilohertz linewidth of an AlGaAs laser by negative electrical feedback*, M. Ohutso et al., *IEEE Journal of Quantum Electronics* 26 (1990) pp231-241]. In this system, the external component is one or more high finesse Fabry-Perot (FP) interferometer. Stabilisation of the laser is achieved by utilising the reflectance characteristics of the interferometer or interferometers to detect FM noise. Electrical feedback is then used to feed back this signal to correct the laser output. However, the system is a complex, free-space system which gives cost disadvantages. Also, because the system operates in free space it is particularly susceptible to external factors such as vibration and dust and also to changes in temperature.

It is an object of the present invention to provide a laser stabilisation apparatus which overcomes these problems. It is a further object of the invention to provide an optical phase detector which may be included in the laser stabilisation apparatus.

According to the present invention, an optical phase detector comprises;

coupling means for receiving two optical inputs and producing two combined optical outputs,

detection means for detecting the two optical outputs and converting the intensity of each of the combined optical outputs into an electrical signal,

means for measuring the difference between the two electrical signals and generating an output difference signal,

whereby the output difference signal may be used to provide an indication of the phase difference between the two optical inputs.

The optical phase detector provides the advantage that it provides an electrical output signal indicative of relative phase difference between the two optical input signals. This cannot be achieved with conventional electrical phase detectors due to the high optical frequencies of the inputs.

Furthermore, although phase difference may be measured optically by interfering two beams to form an interference fringe pattern and measuring the fringe pattern as it moves across a camera face due to a change in the relative phase, this relies on the counting of fringes and interpolation between fringes to measure phase or position accurately. The optical phase detector of the invention is advantageous as the output occurs as a direct electrical signal giving a measure of phase difference.

The coupling means may be any means for producing two combined optical outputs from the two optical inputs, wherein the coupling means produce two intermediate optical outputs from each of the optical inputs, the two intermediate optical outputs produced from each of the optical inputs being in phase quadrature, and wherein the intermediate optical outputs are combined to form the two combined optical outputs. For example, the coupler may be an optical fibre coupler, or other coupled waveguide device, such as in integrated optic waveguide coupler.

In a preferred embodiment, the optical phase detector may comprise a voltage-tuneable electro-optic phase modulator for modulating the phase of one optical input to the optical phase detector, whereby the output difference signal may be maintained at a substantially constant level by varying the voltage applied to the electro-optic phase modulator. Preferably, the constant level is substantially zero volts. In this embodiment, the voltage applied to the electro-optic phase modulator provides an indication of the phase difference between the two optical inputs. This provides the advantage that the optical phase detector is linearised as the voltage required to drive the electro-optic phase modulator is directly proportional to the phase difference between the two optical inputs. It may be preferable to apply this voltage to the electro-optic modulator by means of a feedback loop from the optical phase detector output. The optical phase detector may therefore further comprise means for feeding back the output difference signal to the electro-optic phase modulator, the applied voltage to the electro-optic modulator being varied in response to the output difference signal so as to maintain the difference signal at the substantially constant level.

Preferably, the two optical inputs to the coupling means have substantially equal amplitudes. The coupling means may receive two optical input signals derived from the same source of radiation, for example a single laser. In this arrangement, the optical phase detector provides an electrical output dependent on the phase difference between two optical inputs from the same source of radiation, therefore providing a measure of the relative phase difference. Alternatively, in some applications, the two optical input signals may be derived from two different sources of radiation, preferably having the same amplitude.

The optical phase detector may also comprise polarisation modulation means for modulating the polarisation of at least one of the inputs to the optical phase detector so as to ensure the polarisation of the two inputs is substantially the same. Typically, the polarisation modulation means may be a fibre-optic polarisation modulator.

The optical phase detector may comprise two photodetectors, each one for detecting the intensity of one of the optical outputs and for generating an electrical output signal in response to the corresponding optical output. Preferably, the photodetectors are matched photodetectors.

According to another aspect of the invention, a frequency discriminator apparatus comprises;

an optical phase detector as described herein,

primary coupling means for receiving a primary optical input from a source of radiation and for producing two primary optical outputs, and

means for introducing a relative delay between the two primary optical outputs,

the two primary optical outputs, having a relative delay therebetween, providing the inputs to the optical phase detector.

The primary coupling means may be any means for producing two primary optical outputs from the primary optical input, wherein the two primary optical outputs are in phase quadrature. Preferably, the two primary optical outputs have the same amplitude.

In the frequency discriminator apparatus, the electrical output from the optical phase detector provides a measure of the optical frequency (or wavelength) of an input laser providing the relative delay is known and is substantially stable.

Preferably, the means for introducing a relative delay between the two primary optical outputs comprise two lengths of optical fibre having different optical path lengths. For example, one length of optical fibre may be used through which one of the primary optical outputs is transmitted, with the other primary optical output being transmitted through a negligible length of optical fibre.

The one or more length of optical fibre may be single mode optical fibre, temperature stable single mode optical fibre or temperature stable polarisation maintaining optical fibre. The use of temperature-stable optical fibre provides the advantage that the apparatus has improved temperature stability. Alternatively, or in addition, to achieve temperature stability, the apparatus may be housed in a temperature-stable oven.

The frequency discriminator apparatus, comprising an optical phase detector as herein described, provides a sensor for measuring any one of, for example, temperature, pressure or strain, when that measurand is applied to the optical fibre delay line. Preferably, the frequency discriminator comprises a linearised optical phase detector as here described. It may be advantageous in a sensor application if the relative optical delay in the apparatus is substantially zero.

According to another aspect of the present invention, a laser stabilisation apparatus for stabilising the output from a source of radiation comprises;

the frequency discriminator apparatus as herein described, and

feedback means for feeding the electrical output from the optical phase detector of the frequency discriminator back to the source of radiation.

The laser stabilisation apparatus has an improved performance over known apparatus for stabilising a laser output, and also has several other advantages. For example, the apparatus is less complex than the known apparatus and is therefore cheaper to construct. Also, the laser stabilisation apparatus is capable of stabilising the output from a laser over a narrow to broad frequency range which may be varied depending on requirements.

In one embodiment of the laser stabilisation apparatus, the apparatus may comprise one or more additional frequency discriminator as herein described, each frequency discriminator having corresponding feedback means for feeding back the electrical output from the associated optical phase detector to the source of radiation. The outputs from the optical phase detectors of the different frequency discriminators may be fed back to different control points on the source of radiation.

The apparatus also enables temperature stability, through the use of temperature-stable optical fibre, as well as short term stability to be imparted to the output laser spectrum. The apparatus is relatively insensitive to vibration and dust.

The invention also relates to a method of stabilising the output from a laser, using the laser stabilisation apparatus as herein described.

The optical phase detector of the invention may also be used in other applications, such as laser metrology, in a displacement measurement scheme capable of measuring nanometre displacements. This embodiment of the invention provides an advantage over known displacement measurement schemes which rely on the counting of fringes and interpolation between fringes to measure position accurately.

According to another aspect of the invention, an optical frequency synthesizer comprises;

the laser stabilisation apparatus as herein described, comprising two lengths of optical fibre through which the primary optical outputs are transmitted, the two optical fibres having different optical path lengths, and

an electro-optic phase modulator arranged in the path of one of the lengths of optical fibres,

whereby application of a SAWTOOTH-like voltage waveform to the electro-optic phase modulator gives rise to a variation of the frequency of the laser output.

The optical frequency synthesizer may also comprise a voltage source, providing an SAWTOOTH-like voltage waveform, for applying a voltage to the electro-optic phase modulator.

According to another aspect of the invention, an optical vector voltmeter for comparing an input laser signal and a reference signal comprises;

the optical phase detector as herein described,

a photodetector for receiving the input laser signal and for generating an output signal dependent on the amplitude of the input laser signal,

the output from the electro-optic phase modulator providing a measure of the phase difference between the reference signal and the input laser signal.

According to another aspect of the invention, an optical network analyser for measuring the transmitted or reflected amplitude and phase of a system at a plurality of frequencies comprises;

the optical frequency synthesizer as herein described, for generating a reference signal at a plurality of frequencies, and

the optical vector voltmeter as herein described, for receiving as inputs the reference signal and the signal transmitted or reflected by the system.

In any of aspects of the invention described above, single mode optical fibre, polarisation maintaining optical fibre, temperature stable single mode optical fibre or temperature stable polarisation maintaining optical fibre may be used.

Although aspects of the invention are herein described as in-fibre applications, all aspects of the invention may make use of free space optics in all or some of the optical paths. For example, free space optics may be used in a gas sensor.

The invention will now be described, by way of example only, with reference to the following figures in which;

Figure 1 shows a diagram of the optical phase detector of the present invention,

Figure 2 illustrates the output levels of the detectors of the optical phase detector of Figure 1 as a function of relative optical phase

Figure 3 illustrates the differential output level between the detector outputs shown in Figure 2 as a function of relative optical phase,

Figure 4 shows a diagram of a linearised version of the optical phase detector shown in Figure 1,

Figure 5 shows the linearised optical phase detector shown in Figure 4 including an electrical feedback loop,

Figures 6(a) and 6(b) shows experimental results obtained using the linearised optical phase detector, with feedback, as shown in Figure 5,

Figure 7 shows an example of a practical electrical circuit of the detectors included in the optical phase detector in Figure 1,

Figure 8 shows the laser stabilisation apparatus of the invention, including the optical phase detector shown in Figure 1,

Figure 9 shows phase noise measurements for an unstabilised laser output and a stabilised laser obtained using the laser stabilisation apparatus,

Figure 10 shows the laser stabilisation apparatus shown in Figure 8, and further comprising an electro-optic phase modulator external to the optical phase detector, or a differential amplifier in the feedback loop of the apparatus,

Figure 11(a) shows an example of a SAWTOOTH voltage waveform which may be applied to the phase modulator in the apparatus of Figure 10 to provide an optical frequency synthesizer, and Figure 11(b) shows the variation of phase of the electro-optic phase modulator to which a SAWTOOTH waveform voltage is applied,

Figure 12 shows an experimental result obtained using the apparatus shown in Figure 10,

Figure 13 shows a schematic diagram to illustrate how the optical phase detector shown in Figure 5 may be employed in a sensor,

Figure 14 shows a schematic diagram to illustrate how the optical phase detector shown in Figure 5 may be employed in an optical vector voltmeter,

Figure 15 shows a schematic diagram to illustrate how the optical vector voltmeter shown in Figure 14 and the apparatus shown in Figure 10 may be employed in an optical network analyser for transmission measurement of a system under test,

Figure 16 shows a schematic diagram to illustrate how the optical vector voltmeter shown in Figure 14 and the apparatus shown in Figure 10 may be employed in an optical network analyser for reflection measurement of a system under test, and

Figure 17 shows a schematic diagram of a gas sensor application of the optical phase detector and employing free space optics.

It is the object of one aspect of the invention to provide an optical phase detector capable of producing an electrical output signal dependent on the phase difference, or relative phase, between two optical inputs of substantially the same frequency.

Referring to Figure 1, an optical phase detector, referred to generally as 1, may comprise a 50/50 fibre optic directional coupler 2 for coupling two inputs 3,4. The detector 1 also comprises two optical detectors 5a,5b and a differential amplifier 6. In operation, the two inputs 3,4 are input to the optical phase detector 1 through the directional coupler 2. A 50/50 single mode fibre optic directional coupler has a central portion 10 comprising two coupled optical fibres.

The inputs 3,4 to the coupler are combined by evanescent coupling in this central portion 10 and two combined outputs 11,12 are generated. These combined outputs 11,12 will vary in amplitude (and intensity) depending on the phase difference between the two input signals 3,4. Preferably, the input signals 3,4 have substantially equal amplitudes.

The function of the coupler is to produce two intermediate outputs from each of the two inputs (i.e. four in total) which are then combined to form the two outputs 11,12. Each input signal gives rise to two intermediate optical outputs and it is an important property of the coupler that the two intermediate outputs produced from each of the individual inputs are in phase quadrature (i.e. have a phase difference of substantially 90° therebetween). The intermediate outputs from each of the inputs are combined in pairs to provide the combined outputs 11,12. The coupler may be any coupling means which provides this function. Ideally, this coupler may be a coupled waveguide device, such as a conventional in-fibre coupler, but other coupler devices may be used.

Typically, the two optical inputs 3,4 to the optical phase detector may be derived from the same source, such as a laser (not shown). It is preferable for the optical inputs 3,4 to be taken from the laser output to the phase detector via single mode optical fibre. Alternatively, two beams of radiation may be taken from the laser and coupled to single mode optical fibres, for example by means of lenses, for subsequent input to the optical phase detector 1.

Each of the output signals 11,12 from the coupler 2 is directed to a separate detector 5a,5b which converts the intensity of the respective optical input (i.e. inputs 11,12) into a corresponding electrical output signal 7a,7b. The electrical signals 7a,7b output from the detectors 5a,5b are then passed to a differential amplifier 6 which produces an output 20 proportional to the difference in voltage between the input signals it receives. Preferably, the detectors are matched (i.e. are as identical as possible). For example, they may be made in the same batch or even on the same chip. For clarity, the electrical connections to the detectors are not shown in Figure 1.

The optical phase detector 1 exploits the fact that the two output signals 7a,7b from the detectors 5a,5b depend on the relative phase of the two optical signals 3,4 input to the coupler 2. That is, the detectors 5a,5b and the differential amplifier 6 provide a substantially balanced optical detector circuit (referred to generally as 32) and the voltage output from the differential amplifier 6 gives a measure of the phase difference between the two input signals 3,4. This requires the amplitudes of the inputs 3,4 to be substantially constant. If the amplitudes of the inputs 3,4 are varying, it is possible to measure the amplitudes separately and correct for any variation electrically.

In order to measure the phase difference between two optical inputs 3,4 it is important to ensure the polarisation of the two inputs 3,4 is the same. This may be achieved by including a polarisation controller in the path of one or both of the input signals 3,4. For example, if the input signals 3,4 are coupled to the phase detector 1 from a laser by means of optical fibre a fibre optic polarisation controller may be used in one, or both, of the input pathways 3,4. Alternatively, in an integrated optical phase detector, an integrated optic polarisation modulator may be used. Polarisation-maintaining optical fibres and couplers may be used throughout the optical phase detector 1 also.

This behaviour of the optical phase detector 1 is illustrated in Figures 2 and 3. Figure 2 shows how the outputs 7a,7b from the individual detectors vary with the relative phase between the two optical inputs 3,4. The amplitudes of the output signals 7a,7b from the two detectors 5a,5b vary with relative phase as a squared-sinusoid and are relatively in anti-phase. The optical phase detector 1 therefore provides a DC output voltage which is a measure of the phase difference between the two input signals 3,4.

Figure 3 shows the differential output 20 of the pair of detector outputs 7a,7b which varies sinusoidally with the relative optical phase of the inputs 3,4. In this embodiment of the optical phase detector 1, the output 20 is bipolar and is particularly useful in some applications, as will be described in more detail later. However, a preferred embodiment of the optical phase detector may include an electro-optic phase modulator to provide an optical phase detector having a linearised response.

Typically, an electro-optic phase modulator comprises an optical waveguide on an integrated optic substrate, such as lithium niobate or lithium tantalate or other electro-optic material. By applying a voltage across the waveguide by means of metallic electrodes the phase of radiation passing through the waveguide can be modulated. The response of electro-optic phase modulators comprising a lithium niobate or lithium tantalate substrate is very linear.

Figure 4 shows a manually operated optical phase detector 30 which has a linearised response, comprising an electro-optic phase modulator 35 in one of the input paths 3,4 (input 3 in Figure 4). The electro-optic phase modulator 35 has a linear variation of optical phase with applied voltage 36. If this voltage were manually (or automatically) adjusted to maintain a constant (ideally zero) output 20 from the differential amplifier the voltage 36 applied to the modulator 35 gives a direct linear measure of the relative phase between the optical inputs 3,4.

The electro-optic phase modulator 35 may be placed in the path of one of the inputs 3,4 to the optical phase detector 1. The output 20 from the differential amplifier 6 is then set at a constant level by applying the appropriate voltage to the voltage-tuned electro-optic phase modulator. Preferably, the output may be maintained at zero volts which makes the measurement insensitive to amplitude variations.

As the response of electro-optic phase modulators is very linear, in particular lithium niobate and lithium tantalate devices, the voltage required to set the differential amplifier output to zero gives a useful measure of the relative phase. The voltage adjustment may be made manually, or by means of an electrical feedback loop. Including the electro-optic phase modulator provides the advantage that the phase detector is linearised i.e. the voltage required to tune the electro-optic modulator in order to maintain the differential amplifier at a constant voltage is directly proportional to the measured phase difference. If the difference signal is maintained close to zero the optical phase detector has the further advantage that it is insensitive to amplitude variations in the input optical signals.

Figure 5 shows an embodiment of the linearised optical phase detector 30 which includes an electronic feedback loop, comprising a feedback amplifier 44 and filter 46. As shown in the figure, the feedback amplifier 44 and filter 46 may be separate components, but alternatively the filter may be derived from the amplifier characteristic itself which is carefully designed to be stable. The voltage 36 applied to the electro-optic phase modulator 35 provides the output, which is linearised. The advantage of this embodiment of the phase detector is that it removes the need for a human operator and is relatively fast and accurate in operation. Figures 6(a) and 6(b) show experimental results obtained using the device shown in Figure 5. The measurements were obtained directly from a Tektronix 2430 digital oscilloscope. The solid lines are the best fits to the measured points. This characteristic may be compared with the nonlinear (sinusoidal) response of Figure 3.

A circuit diagram of part of the optical phase detector 1 is shown in Figure 7. In a non-linear optical phase detector 1 (i.e. as shown in Figure 1), the detectors 5a,5b are arranged such that the net output signal 20 varies sinusoidally about zero depending on the relative phase between the inputs 11,12. Hence a bipolar signal 20 is output from the detector (as shown in Figure 3). Typically, the detectors 5a,5b may be reverse biased PIN devices, although any low noise detector may be used. Commercially available optical detectors GAP 60 or GAP 100 may be suitable devices. The value of resistor R_1 (as shown in Figure 7) determines the gain and hence the peak to peak bipolar output voltage. Typically, the voltage (+V, -V) applied across the detectors may be ± 9 Volts.

If the photodetectors 5a, 5b are not quite identical, means for equalising the sensitivity of the photodetectors may be included in the phase detector. It has been found that the bias voltage on one or both detectors may be varied in order to provide a fine adjustment to photodetector sensitivity.

Both the sinusoidal and linearised optical phase detector 1, 30 provide a DC output voltage which is a measure of the phase difference between the two inputs. This cannot be achieved with conventional electrical phase detectors due to the high optical frequencies of the inputs. Furthermore, the optical phase detector of the invention is advantageous as the output occurs as a direct electrical signal giving a measure of phase difference. The detector may therefore be used in a high accuracy displacement measurement apparatus for measuring displacements of the order of a few nanometres. This may be of particular use in laser metrology. For example, the output from the optical phase detector provides a measure of the phase difference between two input signals derived from the same, stable laser, where one of input signals is reflected from a displaced surface or object. The phase difference may be used to provide an indication of the displacement of the surface or object. The input laser may be stabilised by the laser stabilisation apparatus of the invention which will be described later.

The optical phase detector may also be used to phase lock two-independent lasers, for example a high powered tuneable laser and a low power stable laser. This is achieved by inputting laser outputs from two different lasers to the optical phase detector (i.e. as inputs 3 and 4 shown in Figures 1 and 4).

The characteristics of the optical phase detector shown in Figures 2 and 3 may also be exploited in a frequency discriminator. In general terms, a frequency discriminator employs an input signal of constant amplitude and produces an output voltage proportional to, or dependent on, the amount by which the input frequency differs from a fixed frequency.

Referring to Figure 8, the parts enclosed within the dashed line, referred to generally as 60, form a frequency discriminator comprising an optical phase detector 1 (as shown in Figure 1) and a 50/50 fibre optic directional coupler 41 for receiving an output 42 from a laser 43. The discriminator 60 also comprises means for introducing a relative delay between the two output signals 52, 53 from the coupler 41. Conveniently, this may be achieved by means of two lengths of optical fibres 50,51, each for receiving one of the output signals 52,53 from the coupler 41, one optical fibre being longer than the other so as to introduce a relative delay. In practice it is convenient if one of the lengths of optical fibre is very short. Preferably, the one or more length of optical fibre 50,51 may be temperature-stable optical fibre which gives the apparatus improved temperature stability. Alternatively, or in addition, to achieve temperature stability, the apparatus may be housed in a temperature-stable oven. A polarisation modulator, such as an in-fibre polarisation modulator, may be included in either one or both pathways 50,51, as discussed previously.

The function of the frequency discriminator 60 is to split the output of a laser 43 into two substantially equal output beams 52,53 by means of the first coupler 41, delay one signal relative to another and then measure the optical phase difference between the two signals 52,53. This may be done by means of the optical phase detector shown in Figure 1. It cannot be done using conventional electrical phase detectors as the optical frequencies in question are far too high.

One output 53 from the first coupler 41 is connected through an optical fibre 51 to a second 50/50 fibre optic coupler 2, which forms part of the optical phase detector 1. The other output 52 is passed through the longer optical fibre (i.e. a delay line 50) before connection to this coupler 2. As discussed previously, the outputs from the second coupler 2 (incorporated within the optical phase detector 1) vary in level depending on the relative phase of the input signals to the coupler 2. The optical phase detector 1 therefore provides a DC output voltage which depends on the relative phase between the two inputs. For example, if the delay line has a delay of T_d seconds, the phase shift will vary at a rate of 2π radians for every $1/T_d$ change in the input laser signal frequency. The frequency discriminator 60 therefore operates with a control characteristic which repeats every $1/T_d$ change in frequency. As shown in Figure 3, the discriminator output voltage 20 (i.e. the output voltage from the differential amplifier 6) varies sinusoidally with the relative optical phase of the two input signals.

If the optical phase detector is arranged to operate around 0V, a bipolar output signal is produced, as described previously. If the input frequency to the first coupler varies in time, this will result in a change in the bipolar output signal. For an increased laser output frequency, the bipolar output signal from the discriminator will be of one polarity and for a decreased laser output frequency the signal from the discriminator will be of the opposite polarity. The magnitude of the bipolar output depends on the degree of phase shift and hence the frequency shift of the input laser. Typically, the peak to peak voltage may be in the range between ± 0.1 -10 V.

A frequency discriminator has useful applications itself, for example to measure the output spectrum of a laser. The electrical output from the frequency discriminator 60 may be used to provide a measure of the optical frequency (or wavelength) of an input laser as long as the relative delay between fibres 50 and 51 is known and is substantially stable. This does provide a frequency (or wavelength) measurement, although it is an ambiguous one as the phase is only detected modulo 2π . This is, however, a useful measurement over a small frequency range. The delay line length may be adjusted to set the required sensitivity. Ideally, the phase excursion will be kept to within a few degrees around zero to maintain linearity. Alternatively, the linearised optical phase detector 30 (as shown in Figure 5) may be employed within the discriminator 60 to maintain linearity.

The bipolar output signal of the frequency discriminator may also be exploited as a means of correcting for any phase deviation in the laser output 42. Referring again to Figure 8, this correction process may be achieved by means of a laser stabilisation apparatus (within outer dashed line and referred to generally as 70). The laser stabilisation apparatus 70 comprises the frequency discriminator 60 and a feedback circuit. The laser output 42 to be stabilised is split into two signals, preferably of equal amplitude, by the coupler 41. Preferably, the output 42 from the laser 43 is passed through an optical isolator 62 to remove the detrimental effects of any light reflected back into the laser 43. The output 20 from the discriminator 60 is then fed back to the laser 43, so as to vary its frequency, through the feedback circuit. It is important in the laser stabilisation apparatus 70 that the discriminator output 20 is a bipolar output so that a frequency shift in either direction can be corrected to stabilise the laser output 42.

The feedback circuit comprises a control loop amplifier 72 and a loop filter 74. The output 20 from the discriminator 60 is amplified by the control loop amplifier 72 and is then passed through the loop filter 74 to produce an error signal. This error signal may then be used to control the frequency of the laser 43. If the laser 43 has a frequency control, the error signal may be applied to the frequency control point of the laser 43 so as to reduce the phase noise by a corresponding amount, in the corresponding direction. The "stabilised" output 76 from the laser may be taken from the apparatus by using an additional coupler 78 located in the path before the discriminator 60.

In the case of a semiconductor laser, such as a laser diode, the feedback may be applied by varying the laser current, as the laser frequency varies with current due to changes in the effective refractive index with current injection. Alternatively, it is possible to build into a laser cavity a reverse-biased section such that it does not absorb light but changes refractive index with an applied voltage which derives from the discriminator output.

The function of the laser stabilisation apparatus is to reduce the output of the differential amplifier to substantially zero, thus maintaining the laser frequency at one of the stable operating points of the frequency discriminator. The laser will eventually lock to the nearest stable operating point and, once lock is achieved, the system maintains control of the laser frequency at that particular frequency. The system may therefore be used to improve the spectral stability of the input laser.

The following measurements have been obtained for a Lightwave Electronics Series 123 Fibre-coupled Diode-pumped solid state non-planar ring laser controlled by a Series 2000 LNC Laser and Locking Accessory (LOLA). The laser had a frequency control input with a tuning range in excess of 30 MHz and a bandwidth of 100 kHz for small modulation indices and had a quoted linewidth of 5kHz. Figure 9 shows the low frequency spectrum measured at the output from the discriminator and shows the phase noise (dBc/Hz) as a function of offset frequency in free running conditions (o) (i.e. measuring the laser output directly) compared to the phase noise measurements obtained when using the laser stabilisation apparatus 70. The measurements show a considerable improvement in the close-in phase noise performance for a laser which already has a quoted linewidth of around 5 kHz (i.e. spectrally pure).

As lasers with high spectral purity tend to be relatively expensive, the system enables less expensive and spectrally less pure lasers to be improved relatively cheaply and easily. The improvement of low cost semiconductor lasers may therefore also be achieved using this system. The most common, cheap and widely used laser is a laser diode but it has a particularly poor spectral stability, especially in the case of Fabry-Perot etalon designs. The laser stabilisation apparatus may be therefore be particularly useful for improving the spectral stability of these devices, as well as DFB lasers. It may also be used to improve stable lasers which is also very useful, for example in high resolution spectroscopy and in frequency standards. In particular, the degree of phase noise improvement which may be obtained is dictated by the choice of the delay time. Typically, the delay line may introduce a relative delay of up to 10 μ s between the output signals from the first coupler, depending on the range and sensitivity needed to give the required degree of spectral improvement. The delay time must also be chosen so that the open loop gain of the discriminator is reduced to well below unity at frequencies approaching the reciprocal of the delay time. For example, for a delay line of 1 μ s, the open loop gain of the discriminator should be well below unity for input frequencies of around 1 MHz. If lasers, such as laser diodes, have a high noise level at greater offset frequencies a wideband loop (and short delay) must be used.

For lower performance lasers, for example having linewidths of around 1 MHz, much higher loop bandwidths are required. This therefore requires a shorter delay line. A lower discriminator gain may be compensated for by increasing the gain of the control loop amplifier. Johnson noise from the detectors is likely to be the limiting factor in this gain increase.

Usually, laser diodes have two outputs, one from each facet, or mirror, the second output usually being used to monitor power level. However, it may be possible to use the second output as the input to one of the two optical detectors, hence alleviating the need for the first coupler. However, this embodiment may only be used if the two outputs from the laser are strongly correlated.

In an alternative embodiment of the invention, the laser stabilisation apparatus may comprise two or more loops in parallel. For example, a second output may be taken from the laser 43, or a split signal from output 42, and fed through a second loop having a different gain bandwidth from the first feedback loop. Each loop may then be used to feed back and control the input laser. For example, different feedback signals from each loop may be used to control separate temperature and frequency controls points on the laser. Alternatively, the output from the discriminator 60 may be split, with one split signal feeding back to the laser 43 through one control loop amplifier and loop filter arrangement, and the other signal feeding back to a different control port on the laser via a second control loop amplifier and loop filter.

The laser stabilisation apparatus of the present invention is advantageous as it is an in-fibre system and is therefore less susceptible to external factors, such as vibration, temperature changes and dust, as a free space system. This is especially true if temperature-stable optical fibre is used, as discussed previously. The apparatus may also have a higher effective Q-value compared to that which may be obtained with the known device, the Q-value depending on the length of fibre and therefore, indirectly, on the original laser stability. Furthermore, the length of the fibre optic delay line, and hence the relative delay may be selected in order to vary the sensitivity and range depending on the degree of spectral improvement required. The apparatus may be particularly useful for stabilising the output from laser diodes and other forms of laser, for example to allow them to be used more effectively in fibre optic communications systems.

Referring to Figure 10, an electro-optic phase modulator 80 may be included in the laser stabilisation apparatus 70, for example in either of the delay lines 50,51 (delay line 50 in Figure 10). This may be useful if it is required to frequency-modulate, or slowly sweep the frequency of the stabilised laser. This can be achieved by first stabilising the laser 43 so that the output from the differential amplifier 6 of the optical phase detector 1 is maintained at, say, zero volts and then by applying an appropriate voltage waveform to the electro-optic phase modulator 80. The linearity of the phaseshift in the electro-optic phase modulator ensures a high fidelity frequency-modulated output.

An application of this technique may be to sweep the input laser frequency slowly through an atomic absorption line to make precise measurements of the lineshape. This may be especially useful in the measurement of very narrow lines due to the spectral stability of the laser.

The apparatus may also be used to convert the stabilised laser output 76 into a stabilised optical synthesizer. In this application, the voltage waveform applied to the phase modulator 80 may have the form of a "SAWTOOTH" voltage waveform, in which the phase is swept slowly and linearly over 360° and then rapidly switched back through 360° . However, other waveforms may also be used for this application. Suitable waveforms include those which slowly increase with time and then rapidly decrease to the initial voltage level. The increasing level does not therefore have to vary linearly with time, as in the case of a SAWTOOTH waveform. For the purpose of this specification, any waveform having a slowly increasing voltage level with time followed by a rapid switch back through 360° (in the opposite direction) shall be referred to as a SAWTOOTH-like waveform. Typically, the timescale over which the waveform is switched back through 360° will be of the order of nanoseconds.

By way of example, Figure 11(a) shows an example of a SAWTOOTH voltage waveform (as a function of time) which may be applied to the electro-optic phase modulator 80 for this purpose and Figure 11(b) shows the corresponding change in phase of the modulator 80 with time. During the switching process the laser frequency first follows the slow change in voltage waveform (i.e. modulator pulse) but does not follow the rapid reduction in phase by 360° because the feedback loop filter (i.e. 72, 74) will not respond at this speed. In other words, the switch through 360° degrees has no net effect because the laser and feedback loop are unable to respond to a rapid change. In addition, the output of the optical phase detector 1 is unaffected by the change of phase of 360° as its response is periodic with 360° (as shown in Figure 3). The laser output 76 therefore remains at the new frequency. This process may be repeated many times to cover the full tuning range of the laser. A change of frequency in the opposite direction can be achieved by reversing the voltage waveform slope.

Using the apparatus shown in Figure 10, the stabilised laser output 76 can be controlled to any required frequency by applying an appropriate voltage 86 to the phase modulator 80. In some circumstances this is useful, for example it allows the response over a small frequency range to be measured with a continuous sweep rather than as a series of frequency intervals.

As an alternative to an electro-optic phase modulator, a differential amplifier may be included in the feedback loop to provide a similar laser-tuning function. For example, referring to Figure 10, a differential amplifier 82 may be included in the signal pathway at X. Alternatively, the differential amplifier may form part of the control loop amplifier 72 itself or may be placed in the path prior to the control loop amplifier 72. In this arrangement, rather than maintaining the output 20 from the discriminator 60 at 0V, the input 83 to the differential amplifier 82 may be set to a constant value say, 1 V. The differential amplifier 82 in the feedback loop measures the differential between 1 V and the output voltage from the discriminator 60 after passing through the control loop amplifier 72 and loop filter 74. The differential output 84 is then fed back to control the input laser 43. This would also allow a frequency modulation capability. By this means the laser may be swept in frequency enabling, for example, measurement of narrow spectral line widths and shapes.

The differential amplifier 82 may be used instead of the electro-optic phase modulator 80 and is a cheaper approach. It may be improved by using a linearised optical phase detector 30 (as shown in Figure 5) in place of an optical phase detector 1 having a nonlinear response (as shown in Figures 1, 8 and 10). The use of the electro-optic phase modulator 80 is the preferred approach, however, and has been built and tested in the laboratory.

Figure 12 shows the results obtained using the optical synthesizer shown in Figure 10, including the electro-optic modulator 80. The figure comprises eight spectra measured on an electrical spectrum analyser by mixing the optical synthesizer output at 76 with a stable fixed laser frequency. In this demonstration the discriminator differential delay is 1 microsecond, so successive laser frequencies are 1 MHz apart. However, to provide an intelligible plot the spectra were taken every ten "cycles" of the phase-modulator (i.e. every ten SAWTOOTH waveform cycles and 10 MHz intervals). The scales on the plot shown in Figure 11 are single sideband phase noise dBc/Hz at 10 dB/division (vertically) and 10 MHz/division (horizontally).

Figure 13 shows how the linearised optical phase detector 30 of the present invention (as shown in Figure 4) may be used in sensor applications where the measurand modifies the properties of optical fibre 50 (or 51). For example, the sensor may be used to measure any one of temperature, pressure or strain. For example, referring to Figure 13, if the output 20 from the differential amplifier 6 is set to zero volts by varying the voltage 36 applied to the electro-optic phase modulator 35, any variation in temperature (or other measurand) of the optical fibre delay line 50 will give rise to a change of phase, hence the output from the phase detector will vary. The amount by which the voltage 36 on the electro-optic modulator 35 varies to maintain the output 20 from the differential amplifier 6 at zero (or very close to zero) provides an indication of the variation in temperature (or other measurand).

Although it may be advantageous to use temperature stable optic fibre throughout the sensor, for a temperature sensor application the use of temperature stable optical fibre for the delay line 50 is not appropriate.

In this arrangement a stable laser input is required. Such arrangements may also be used to sense other variations such as pressure or strain. In such schemes a stable input laser 43 should be used. A stabilised laser input may be achieved by using the laser stabilisation apparatus of the present invention, as described previously.

In the sensor application, as distinct from the frequency discriminator application, the two optical fibres 50,51 may have substantially the same delay, rather than having a relative delay therebetween. In some circumstances this may be of benefit. For example, if measuring the pressure on fibre 50, any temperature variation will be common to both fibres 50 and 51 and will therefore cancel if the delays are equal. It may also be particularly appropriate to implement the sensor as a free-space arrangement, rather than an in-fibre apparatus, as will be described later.

Referring to Figure 14, the linearised optical phase detector (as shown in Figure 4) may also be employed in an optical vector voltmeter 90 which operates at optical frequencies. The optical vector voltmeter comprises a linearised optical phase detector 30 (enclosed within the dashed line). The function of the vector voltmeter is to take two inputs 92,94 and to generate two outputs, one of which (output 100) is the amplitude of the unknown input and the other of which (output 102) is the phase of the unknown input signal 92 relative to that of the reference input 94. The unknown input signal 92 is split and one part is input to a detector 96 to provide the amplitude output 100. The second part 93 of the split input signal is input to the linearised optical phase detector 30, along with a reference input signal 94. The output from the differential amplifier 6 is fed back to the electro-optic phase modulator 35 via a feedback amplifier and filter 44, 46. The voltage applied to the electro-optic phase modulator 35 is adjusted, via the feedback loop, to maintain the differential amplifier 6 at a constant value, very close to zero. The electro-optic phase modulator input voltage provides the phase output 102. This gives a direct linear measure of the relative phase between the unknown input 92 and reference input 94.

Figure 15 shows a schematic diagram to illustrate how the optical vector voltmeter 90 shown in Figure 14 and the apparatus shown in Figure 10 may be employed in an optical network analyser for transmission measurement of a system under test (e.g. an optical fibre of unknown properties). The optical network analyser is similar to the optical vector voltmeter, except that it provides a synthesised frequency input to the system under test 110 and typically may measure the transmitted amplitude and phase of the system 110 at a series of frequencies as the optical frequency synthesizer 108 is stepped and/or swept in frequency.

Referring to Figure 15, the optical network analyser comprises an optical synthesizer 108 whose output is split. The operation of the optical synthesizer is described above with reference to Figure 10. The stabilised laser output 76 shown in Figure 10 provides the optical synthesizer output to be split. One part of the split signal 76a is transmitted to the system under test 110 and is transmitted 92 to an optical vector voltmeter 90 (input SYS) as described above (i.e. input signal 92 in Figure 13 is transmitted to the optical vector voltmeter 90). The other part of the split signal 76b is input to the reference port (input REF) of the optical vector voltmeter 90 (i.e. reference signal 94 in Figure 13). The outputs 100, 102 from the optical vector voltmeter 90 form the network analyser outputs. Typically, measurements may be made over a range of optical frequencies (by sweeping and/or stepping the optical synthesizer, as described previously). Other properties, such as group delay, can be calculated digitally using the phase and frequency measurements. Results may be displayed on a VDU, or in digital form.

A variety of other measurements are also possible. For example the amplitude and phase of signals reflected by a system under test 110 may be measured using the optical network analyser shown in Figure 16 which is essentially a rearrangement of the optical network analyser shown in Figure 15. In this embodiment, the input signal 76 is transmitted (via a directional coupler 112) to the system under test 110 and provides a reference signal (REF) to the optical vector voltmeter 90. However, in this embodiment, the signal 114 reflected back from the system 100 provides the other input to the optical vector voltmeter 90 via the coupler 112. In practice, the system will also be terminated by a load, T.

It may be preferable to use temperature stable fibres throughout the apparatus of the present invention (e.g. the laser stabilisation system, the optical synthesizer, the frequency discriminator, the optical vector voltmeter, the optical network analyser, the optical phase detector or in sensor applications), both for connecting optical fibres used throughout the apparatus as well as the one or more delay lines 50,51. Temperature stable fibre is commercially available. The use of temperature stable fibres enables the frequency of the laser output to be stabilised to a higher degree as changes in ambient temperature will have a reduced effect on the optical delay paths. Alternatively, the fibres may be placed in a temperature controlled environment, or the optical path length may include an auxiliary temperature dependent path in series with the fibre in order to maintain a constant delay period. Alternatively, or in addition for extra stability, the apparatus may be operated in a temperature stable oven. Polarisation maintaining optical fibre, temperature stable single mode optical fibre or temperature stable polarisation maintaining optical fibre may also be used.

Although most optical measurements of the kind herein described are invariably performed using fibre optics, the medium used in fibre optic communications, there are some circumstances in which applications of the kind described may be performed using free space optics. The apparatus shown in the various aspects of the present invention can be implemented in this way. For example, in a gas sensor applications the presence of a gas species in air can be detected through dispersion associated with an absorption line since the dispersion causes an actual phase shift. Referring to Figure 17, the apparatus shown in Figure 13 is alternatively implemented by employing laser beams in free space (as opposed to in-fibre) with cube beam splitters 150, 152. The beam splitter 150 corresponds to coupler 41 (e.g. as shown in Figure 13) and coupler 152 is corresponds to coupler 2 forming part of the phase detector (e.g. as shown in Figure 1).

The sensor shown in Figure 17 also comprises mirror 160, 162 and 164 to perform beam directing functions and lenses 170,172 which focus incident radiation onto detectors 5a,5b forming part of the phase detector. As discussed previously, in this application the two free space paths 140 and 142 (corresponding to paths 50 and 51 in Figure 13) may be of substantially equal length, one containing pure air and one contaminated by gas. Typically, the paths 140, 142 may be hollow tubes.

Claims

1. An optical phase detector (1; 30) comprising;

coupling means (2) for receiving two optical inputs (3,4) and producing two combined optical outputs (11,12),

detection means (32) for detecting the intensity of the two combined optical outputs and converting the intensity of each of the combined optical outputs (11,12) into an electrical signal, and

means (60) for measuring the difference between the two electrical signals and generating an output difference signal (20),

whereby the output difference signal may be used to provide an indication of the phase difference between the two optical inputs (3,4).

2. The optical phase detector of claim 1, wherein the coupling means (2) produce two intermediate optical outputs from each of the optical inputs (3,4), the two intermediate optical outputs produced from each of the optical inputs being in phase quadrature, and wherein the intermediate optical outputs are combined to form the two optical outputs (11,12).

3. The optical phase detector of claim 1 or 2, and further comprising;

a voltage-tuneable electro-optic phase modulator (35) for modulating the phase of one optical input to the optical phase detector, the electro-optic phase modulator having a substantially linear response,

whereby in use the output difference signal is maintained at a substantially constant level by varying the voltage (36) applied to the electro-optic phase modulator (35), the applied voltage providing an indication of the phase difference between the two optical inputs (3,4).

4. The optical phase detector of claim 3, and further comprising means (44, 46) for feeding back the output difference signal to the electro-optic phase modulator (35), the applied voltage to the electro-optic modulator being varied in response to the output difference signal so as to maintain the difference signal at the substantially constant level.
 5. The optical phase detector of claim 4, wherein the substantially constant level is zero volts.
 6. The optical phase detector of any of claims 1-5, wherein the optical inputs (3,4) have substantially equal amplitudes.
 7. The optical phase detector of any of claims 1-5 wherein the two optical signals (3,4) are obtained from the same source of radiation.
 8. The optical phase detector of any of claims 1-5 wherein the two optical signals (3,4) are obtained from different sources of radiation.
 9. The optical phase detector of any of claims 1-5, comprising an optical fibre coupler (2) for receiving the two optical inputs (3,4).
 10. The optical phase detector of any of claims 1-5, and further comprising polarisation modulation means for modulating the polarisation of at least one of the inputs to the optical phase detector so as to ensure the polarisation of the two inputs is substantially the same.
 11. The optical phase detector of claim 10, wherein the polarisation modulation means is a fibre-optic polarisation modulator.
-
12. The optical phase detector of any of claims 1-5, comprising two photodetectors (5a,5b), each one for detecting the intensity of one of the two optical outputs (11,12) and for generating an electrical output signal (7a,7b) in response to the corresponding optical output (11,12).
 13. The optical phase detector of claim 12 wherein the photodetectors (5a,5b) are matched.

14. A frequency discriminator apparatus (60) comprising the optical phase detector (1;30) of any of claims 1-5 and further comprising;
- input coupling means (41) for receiving a primary optical input (42) from a source of radiation (43) having a frequency, and for producing two primary optical outputs (52, 53),
- means (50,51) for introducing a relative delay between the two primary optical outputs (52, 53),
- the two primary optical outputs, having a relative delay therebetween, providing the inputs (3,4) to the optical phase detector (1; 30).
15. The frequency discriminator apparatus of claim 14, wherein the primary coupling means produce two primary optical outputs from the primary optical input, wherein the two primary optical outputs are in phase quadrature.
16. The apparatus of claim 14 wherein the means for introducing a relative delay between the two primary optical outputs comprises two lengths of optical fibre (50,51) having different optical path lengths.
17. The apparatus of claim 14, wherein the means for introducing a relative delay between the two primary optical outputs comprises one length of optical fibre through which one of the primary optical outputs is transmitted.
18. The apparatus of claim 16 or 17 wherein the one or more length of optical fibre is any one of single mode optical fibre, temperature stable single mode optical fibre or temperature stable polarisation maintaining optical fibre.
-
19. A sensor comprising the apparatus (60) of claim 14 and including the optical phase detector (30) of claim 4.

20. A sensor comprising the apparatus (60) of claim 14, wherein the relative optical delay is substantially zero.

21. The sensor of claim 20 for measuring any one of a variation in temperature, pressure or strain applied to an optical fibre (50) forming part of the sensor.

22. Laser stabilisation apparatus (70) for stabilising the output (42) from a source of radiation (43) comprising,

the frequency discriminator apparatus (60) of claim 14, including the optical phase detector (1) of claim 1, and

feedback means (72, 74) for feeding back the electrical output (20) from the optical phase detector (1) of the frequency discriminator (60) to the source of radiation (43).

23. The laser stabilisation apparatus (70) of claim 22 comprising one or more additional frequency discriminator apparatus (60) as in claim 14, each frequency discriminator having corresponding feedback means (72, 74) for feeding back the electrical output from the associated optical phase detector to the source of radiation (43).

24. The laser stabilisation apparatus (70) of claim 23, wherein the outputs from the optical phase detectors of the different frequency discriminators feed back to different control points on the source of radiation (43).

25. An optical frequency synthesizer comprising;

the laser stabilisation apparatus (70) of claim 22, comprising two lengths of optical fibre (50,51) through which the primary optical outputs (52,53) are transmitted, the two optical fibres having different optical path lengths, and

an electro-optic phase modulator (80) arranged in the path of one of the lengths of optical fibres,

whereby application of a SAWTOOTH-like voltage waveform to the electro-optic phase modulator (80) gives rise to a variation of the frequency of the laser output.

26. The optical frequency synthesizer of claim 25 and further comprising a voltage source, providing a SAWTOOTH-like voltage waveform, for applying a voltage to the electro-optic phase modulator (80).

27. An optical vector voltmeter (90), for comparing an input laser signal (92) and a reference signal (94) comprising;

the optical phase detector (30) of claim 4 or 5, and

a photodetector (96) for receiving the input laser signal (92) and for generating an output signal dependent on the amplitude of the input laser signal (92),

the output from the electro-optic phase modulator providing a measure of the phase difference between the reference signal (94) and the input laser signal (92).

28. An optical network analyser for measuring the transmitted or reflected amplitude and phase of a system (110) at a plurality of frequencies comprising;

the optical frequency synthesizer of claim 25, for generating a reference signal (76) at a plurality of frequencies, and

the optical vector voltmeter (90) of claim 27, for receiving as inputs the reference signal (76) and the signal transmitted or reflected by the system (110).

Abstract

An optical phase detector comprising coupling means for receiving two optical inputs and for producing two combined optical. The optical phase detector also comprises detection means for detecting the two combined optical outputs and converting each of the optical outputs into an electrical signal, and means for measuring the difference between the two electrical signals and generating an output difference signal. The output difference signal may be used to provide an indication of the phase difference between the two optical inputs. Preferably, the optical phase detector may comprise a voltage-tuneable electro-optic phase modulator for modulating the phase of an optical input to the optical phase detector to provide a linearised response. In this arrangement the output difference signal may be maintained at a substantially constant level by varying the voltage applied to the electro-optic phase modulator, the applied voltage providing an indication of the phase difference between the two optical inputs. Applications of the optical phase detector include a frequency discriminator, a laser stabilisation apparatus and a sensor for measuring variations in temperature, pressure or strain. The frequency discriminator comprises an optical phase detector and means for introducing a relative delay between the two primary optical outputs. The laser stabilisation apparatus comprises one or more frequency discriminator and associated means for feeding back the optical phase detector output to the laser. An electro-optic phase modulator may also be included in the laser stabilisation apparatus. This embodiment of the invention may be used to sweep and/or step the frequency of an input laser or may be used to measure spectral line widths. The optical phase detector may also be used in an optical vector voltmeter or in an optical network analyser.

[Figure 5 should accompany the abstract]

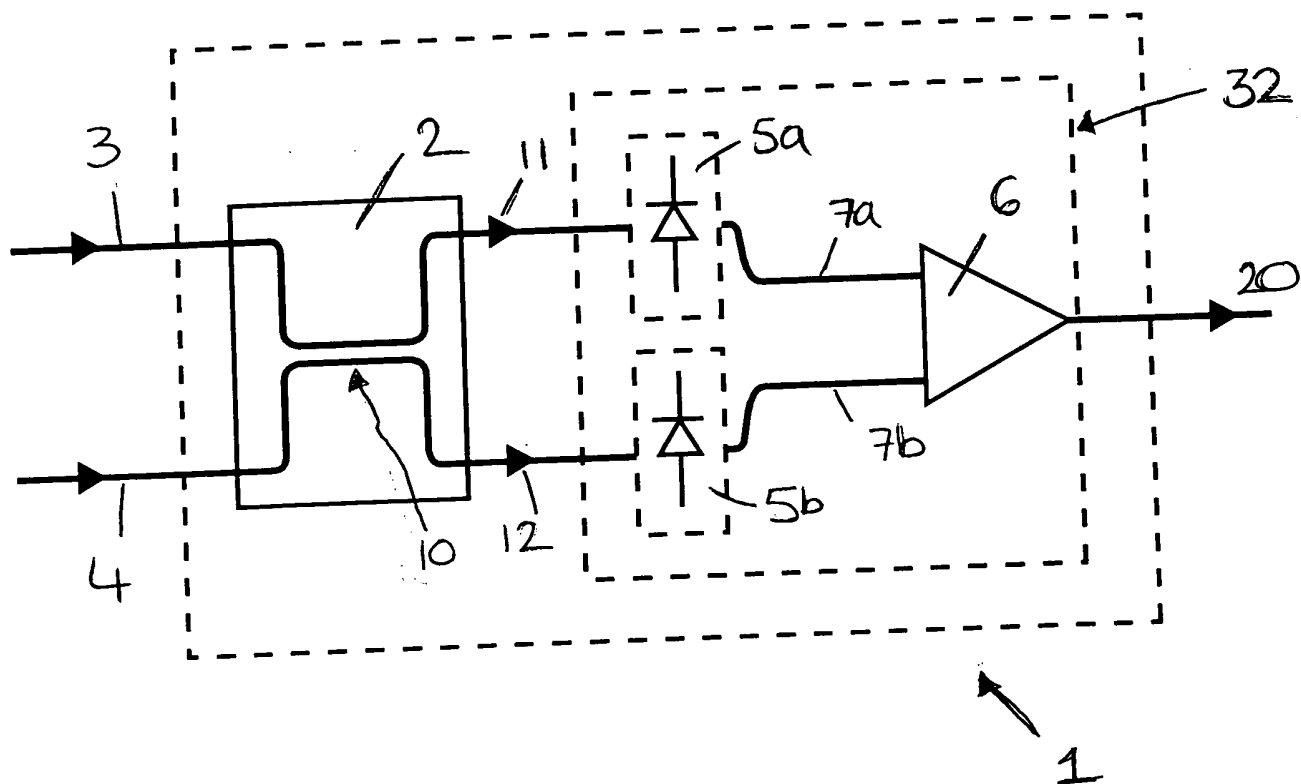
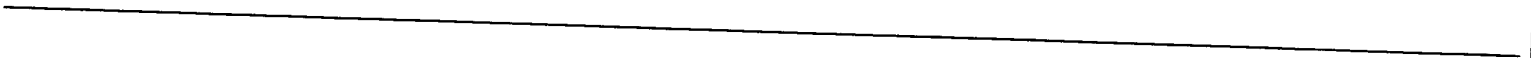


FIGURE 1

NOT TO BE AMENDED



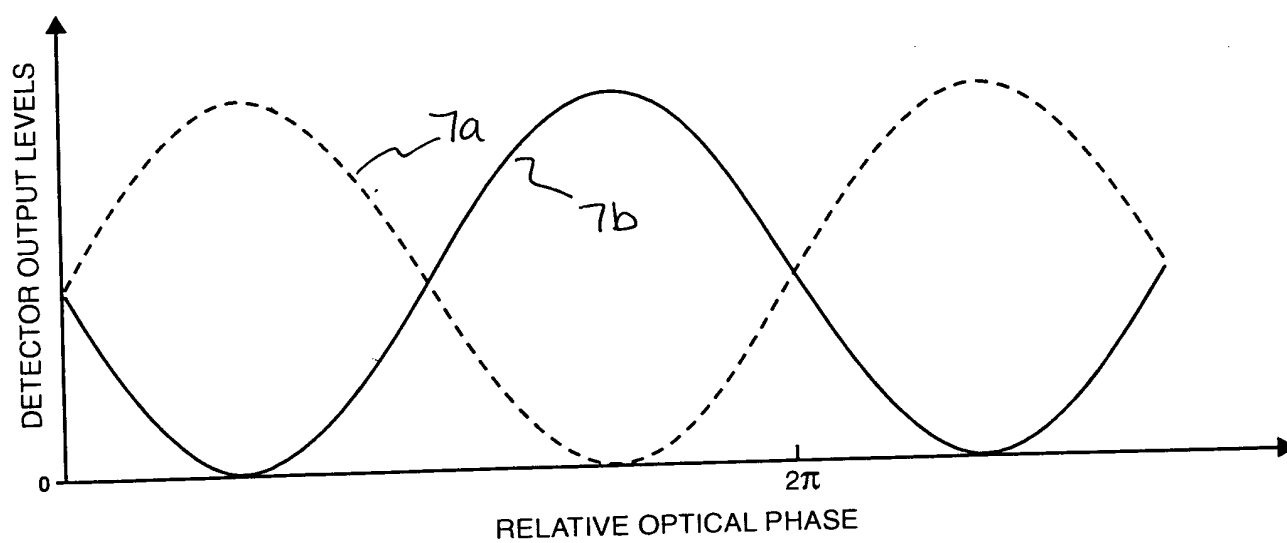
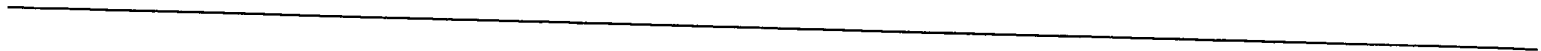


FIGURE 2

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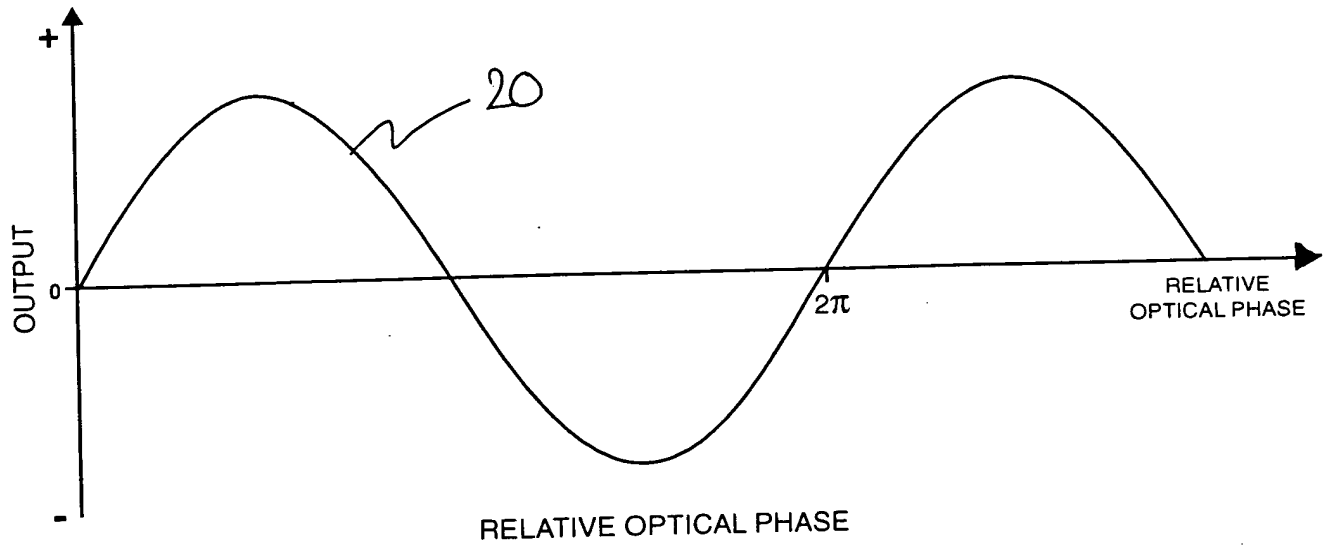
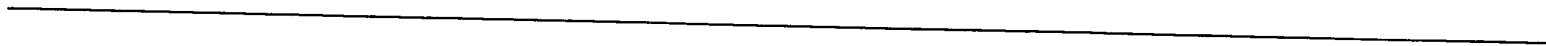


FIGURE 3

UNCLASSIFIED



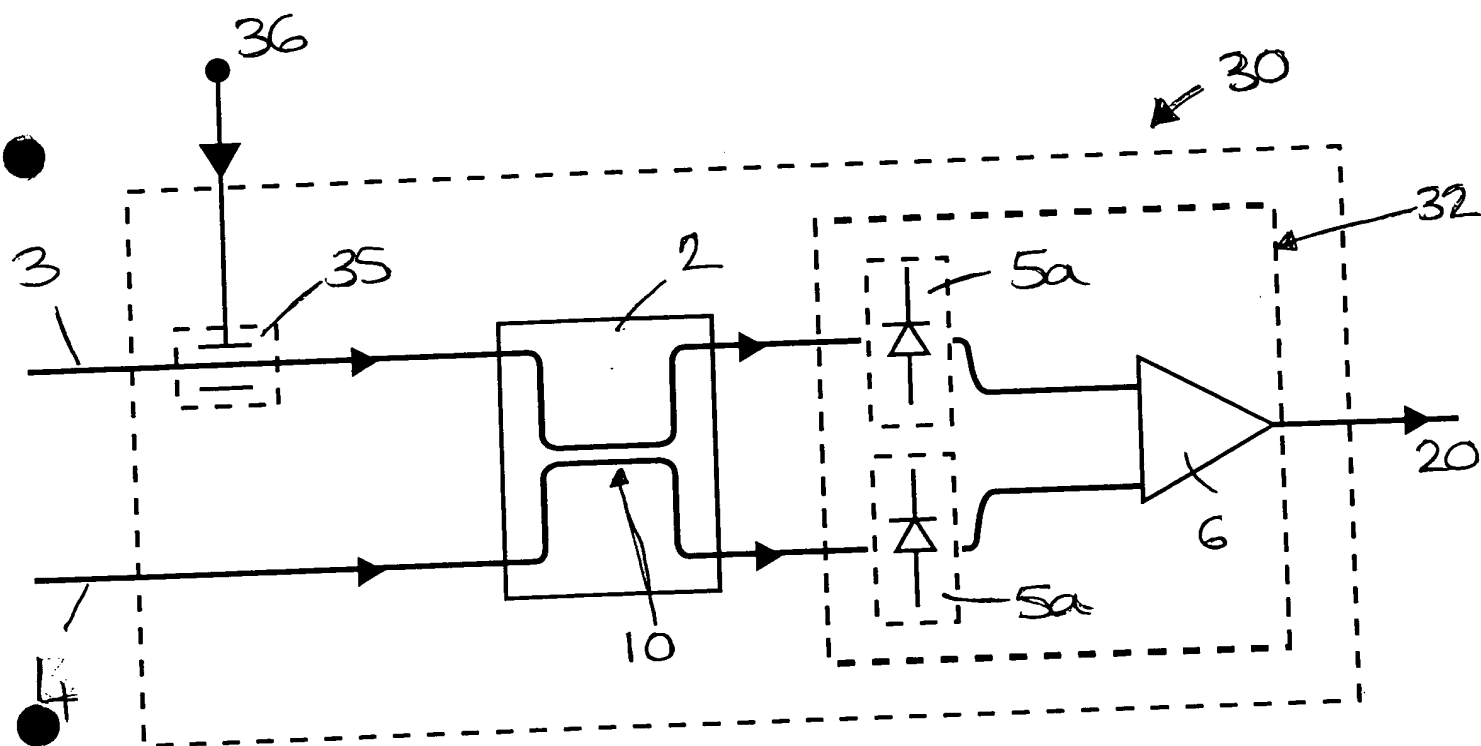
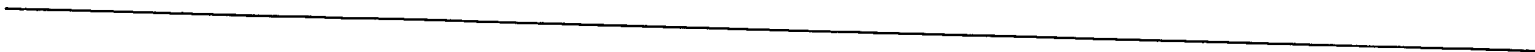


FIGURE 4

NOT TO BE AMENDED



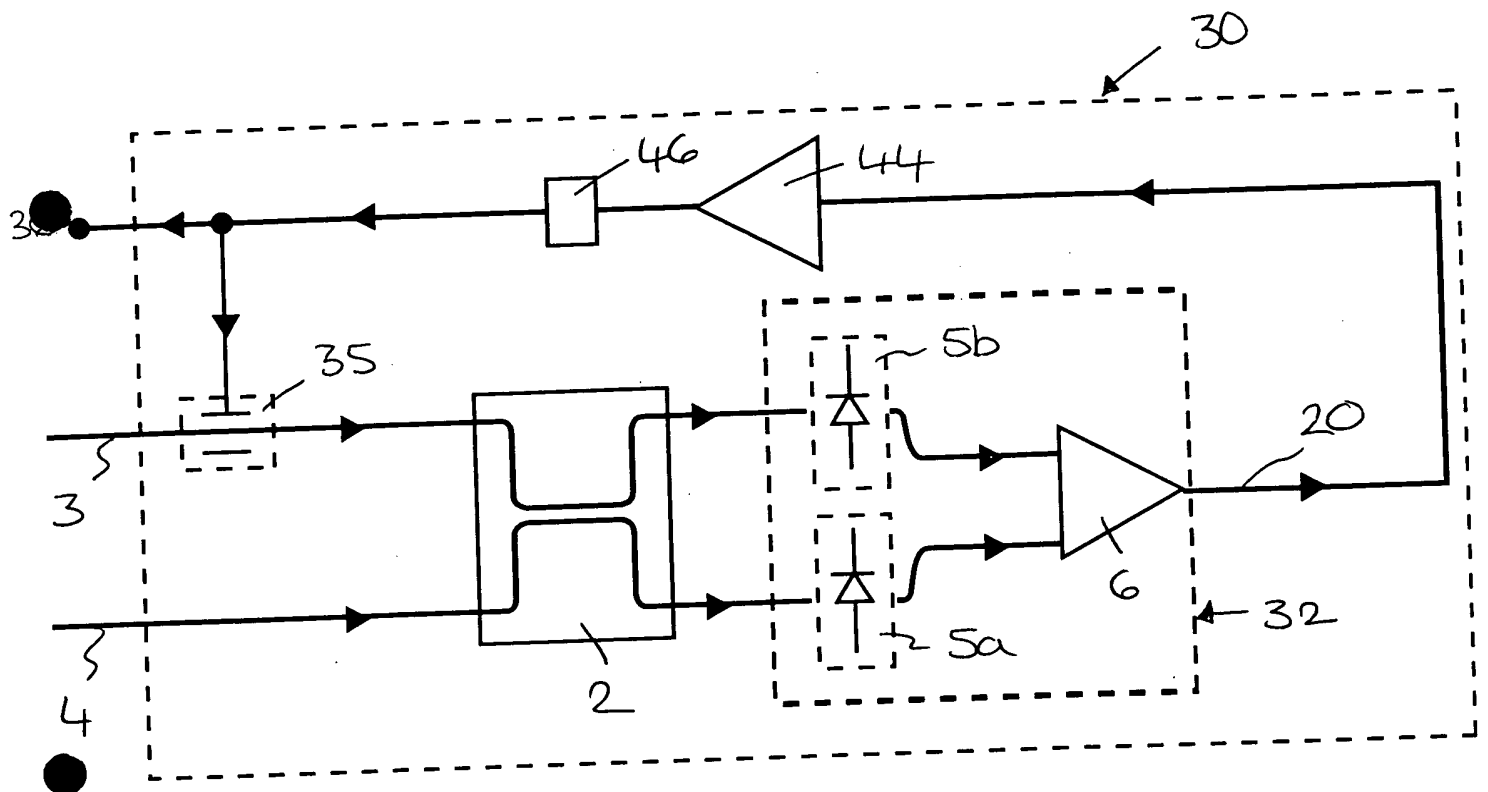
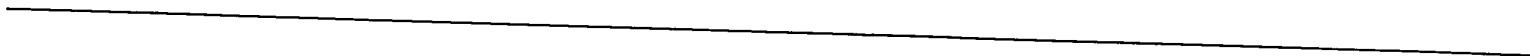
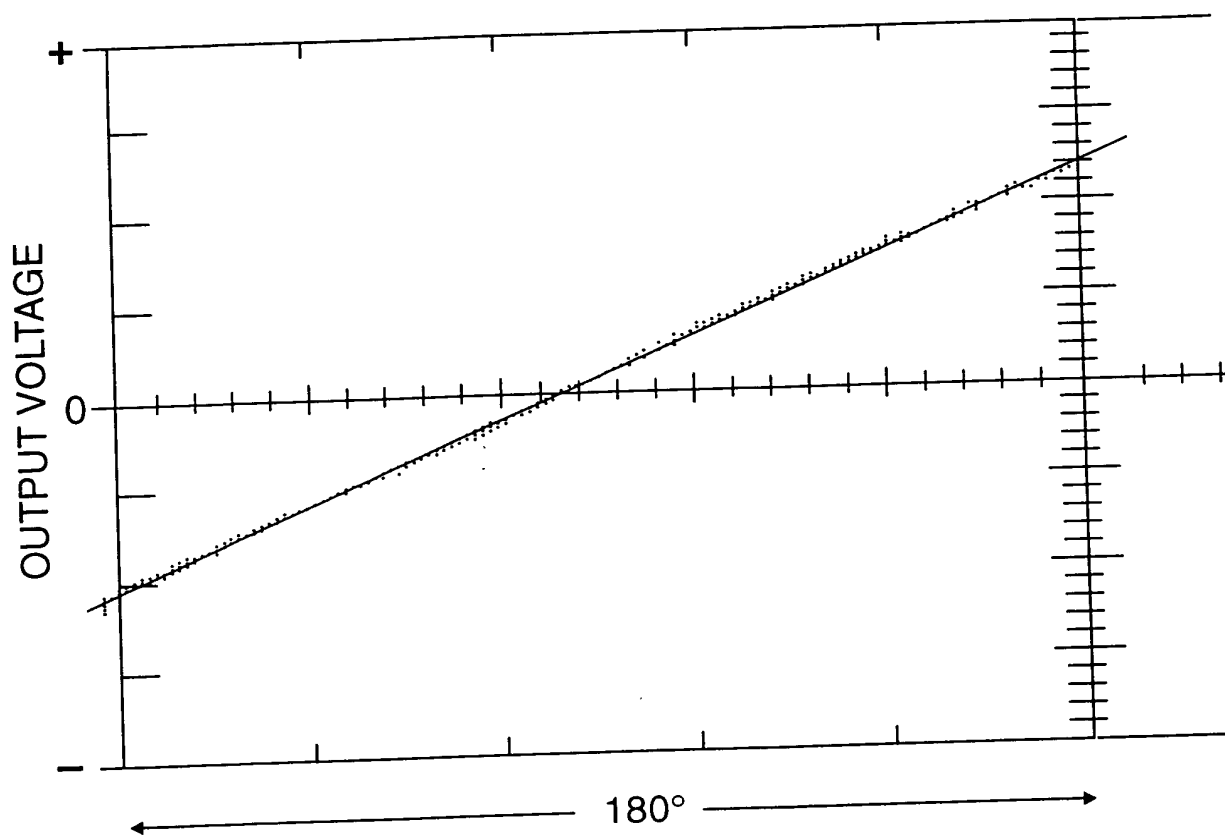


FIGURE 5

NOT TO BE REPRODUCED

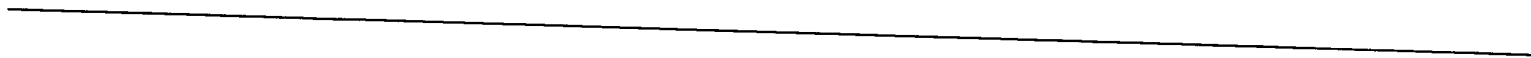


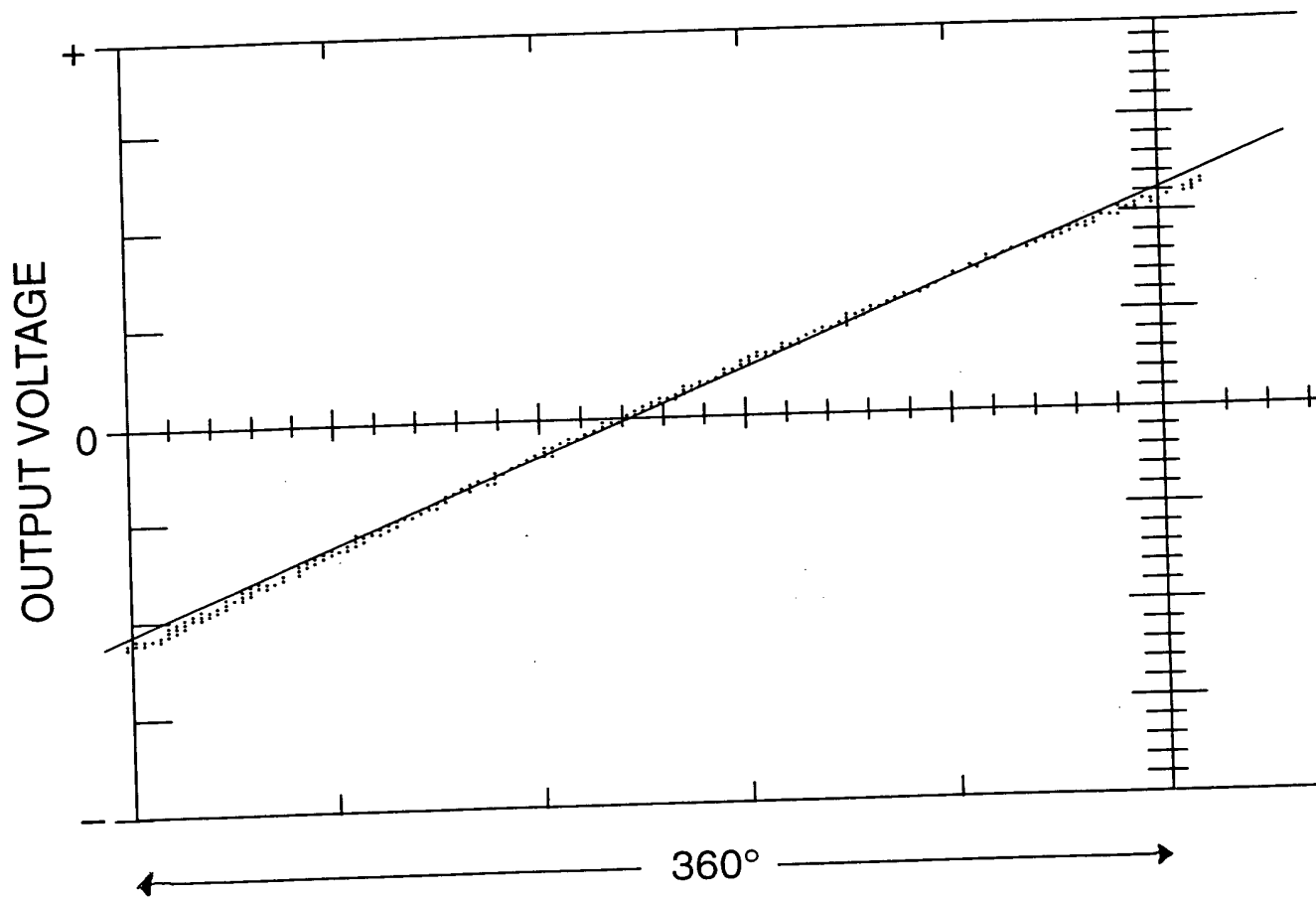


RELATIVE PHASE

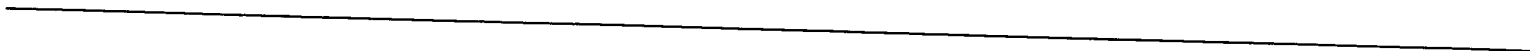
FIGURE 6(a)

— 100% —





RELATIVE PHASE
FIGURE 6 (b)



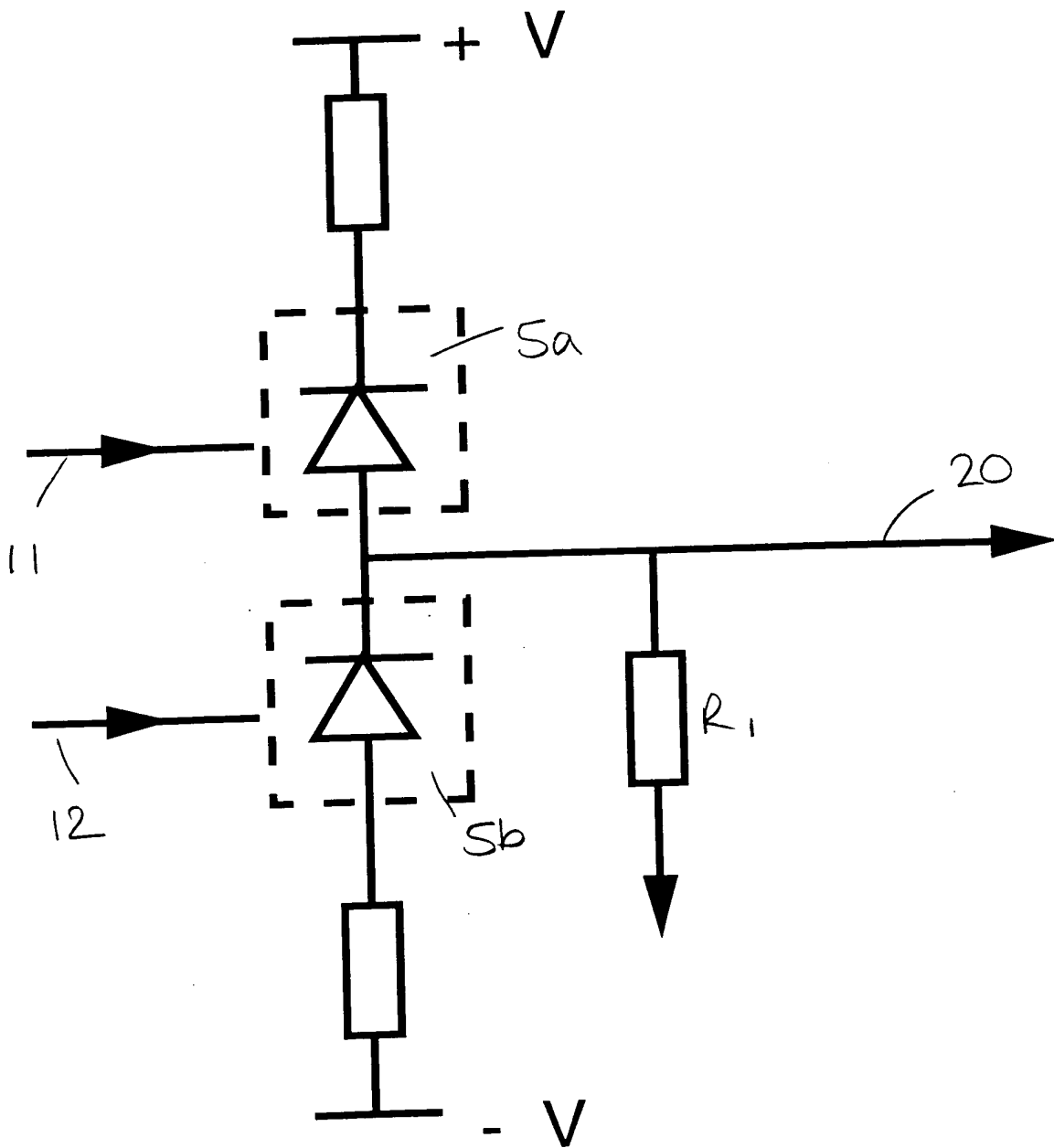
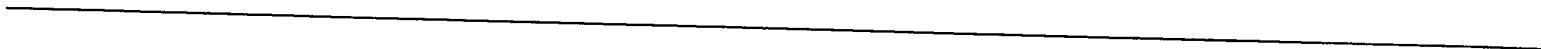


FIGURE 7

NOT TO BE AMENDED



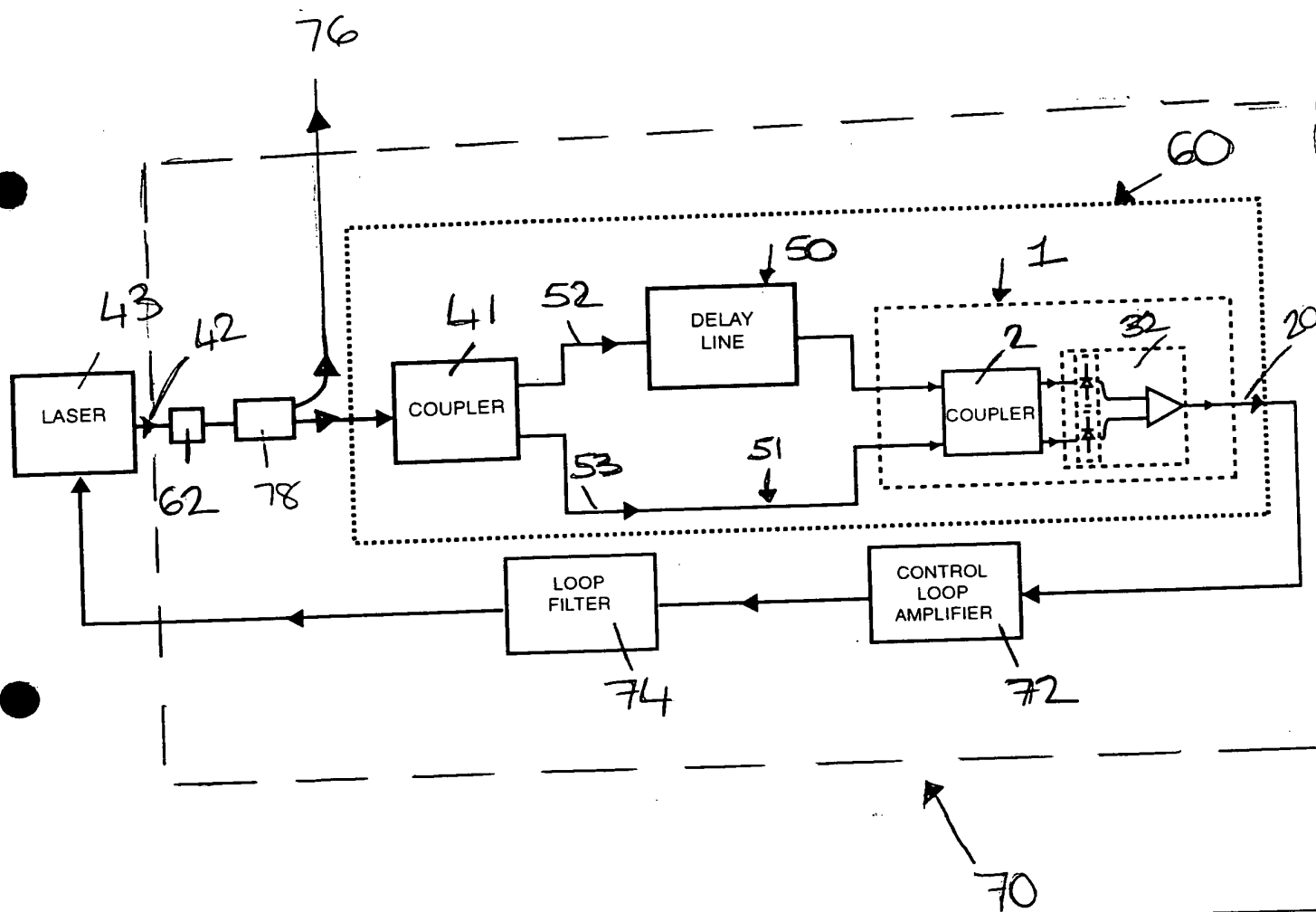
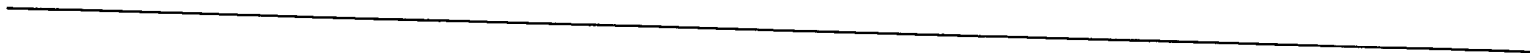


FIGURE 8

UNCLASSIFIED



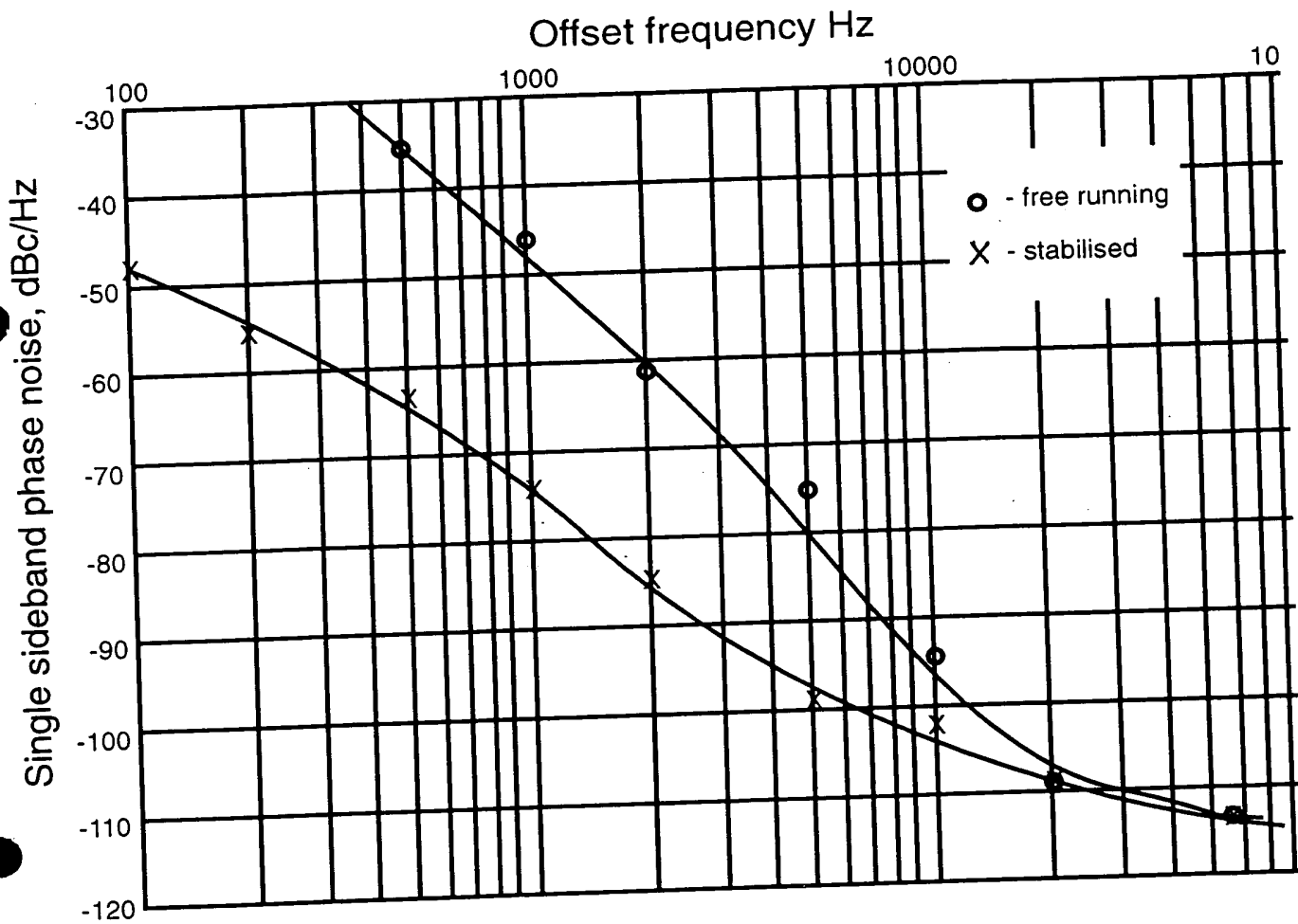
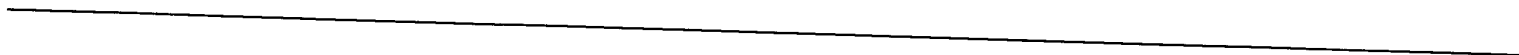
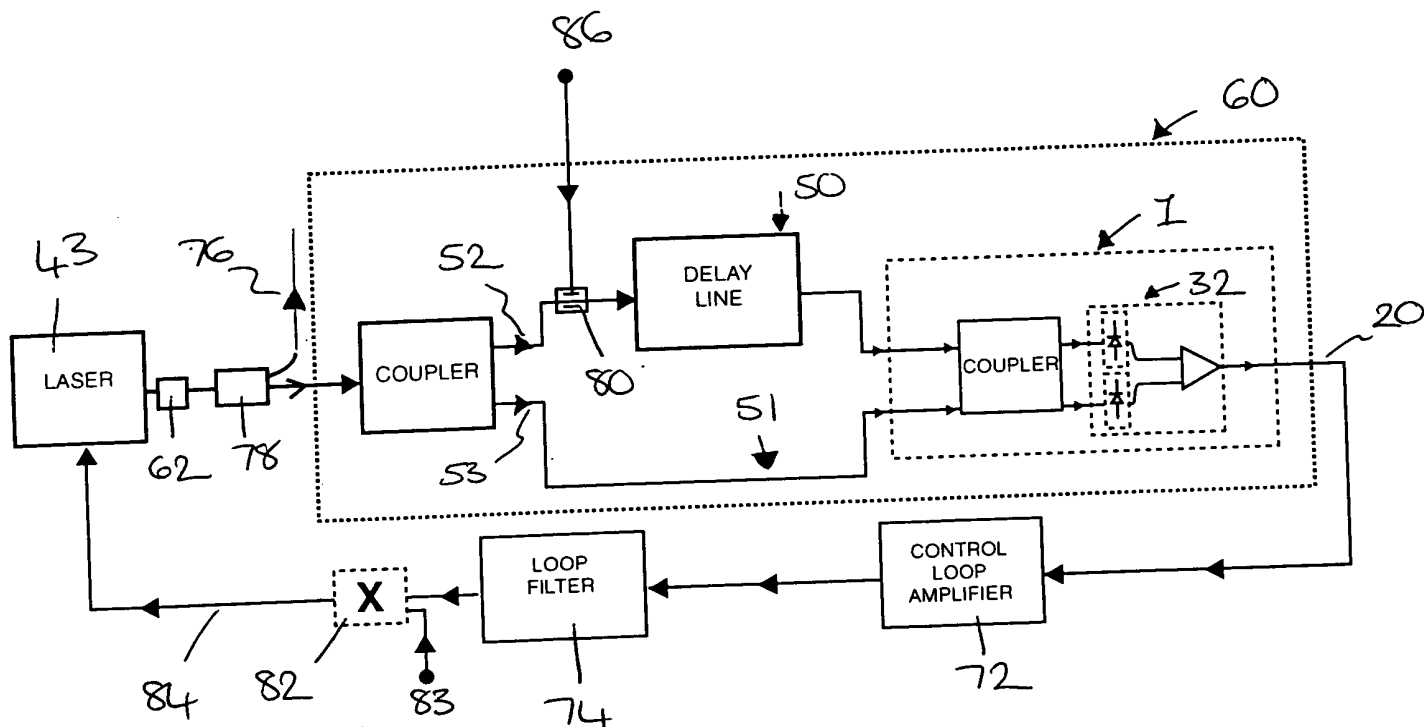
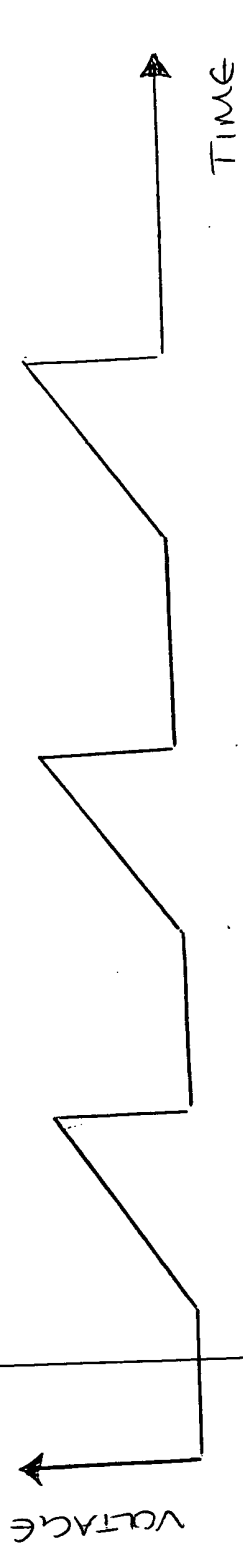


FIGURE 9

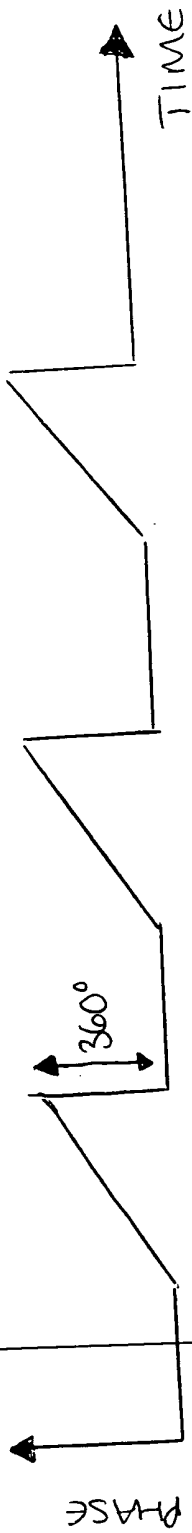




NOT TO BE AMENDED



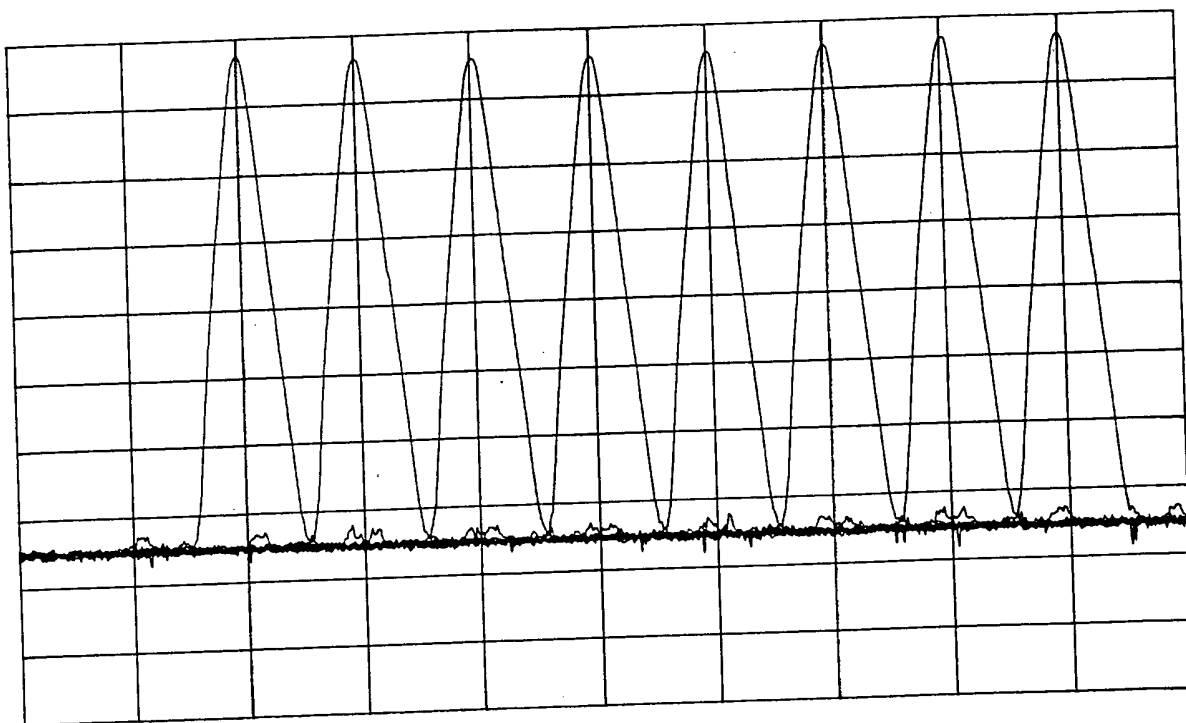
(a)



(b)

FIGURE 11

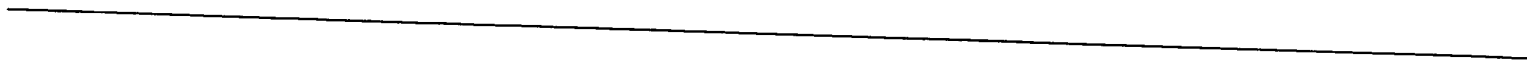
dBc/HZ



FREQUENCY

FIGURE 12

NOT TO BE AMENDED



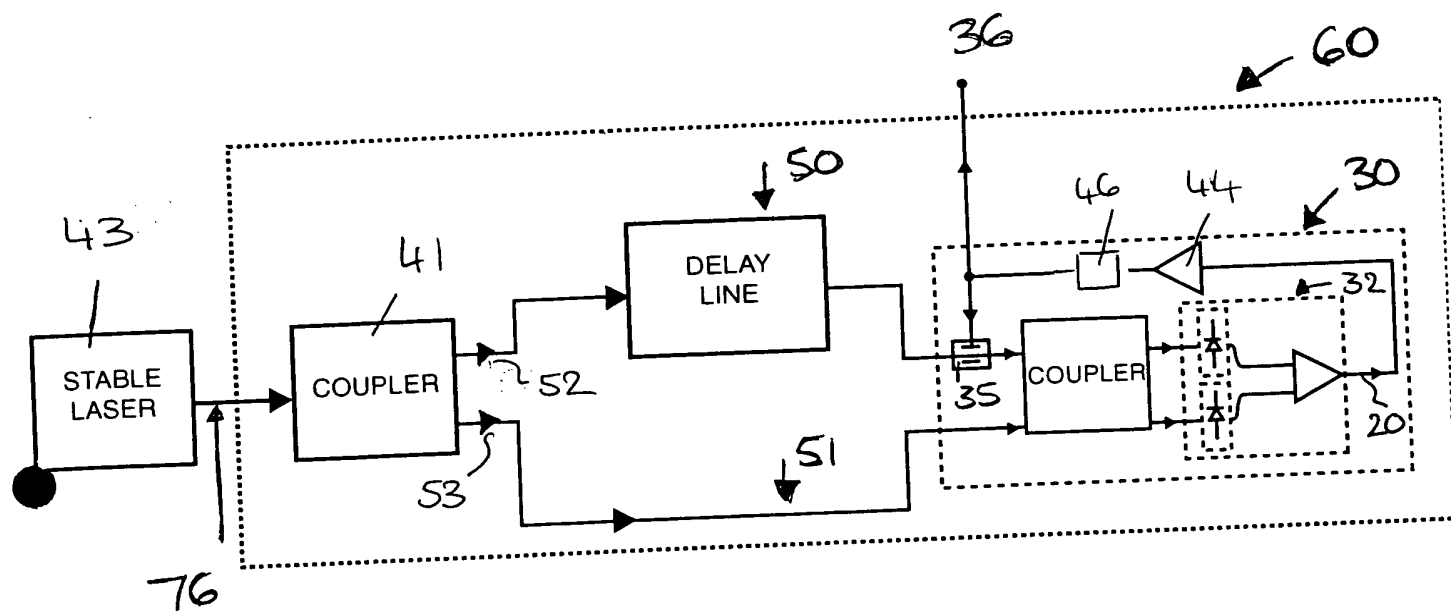


FIGURE 13

NOT FOR REPRODUCTION

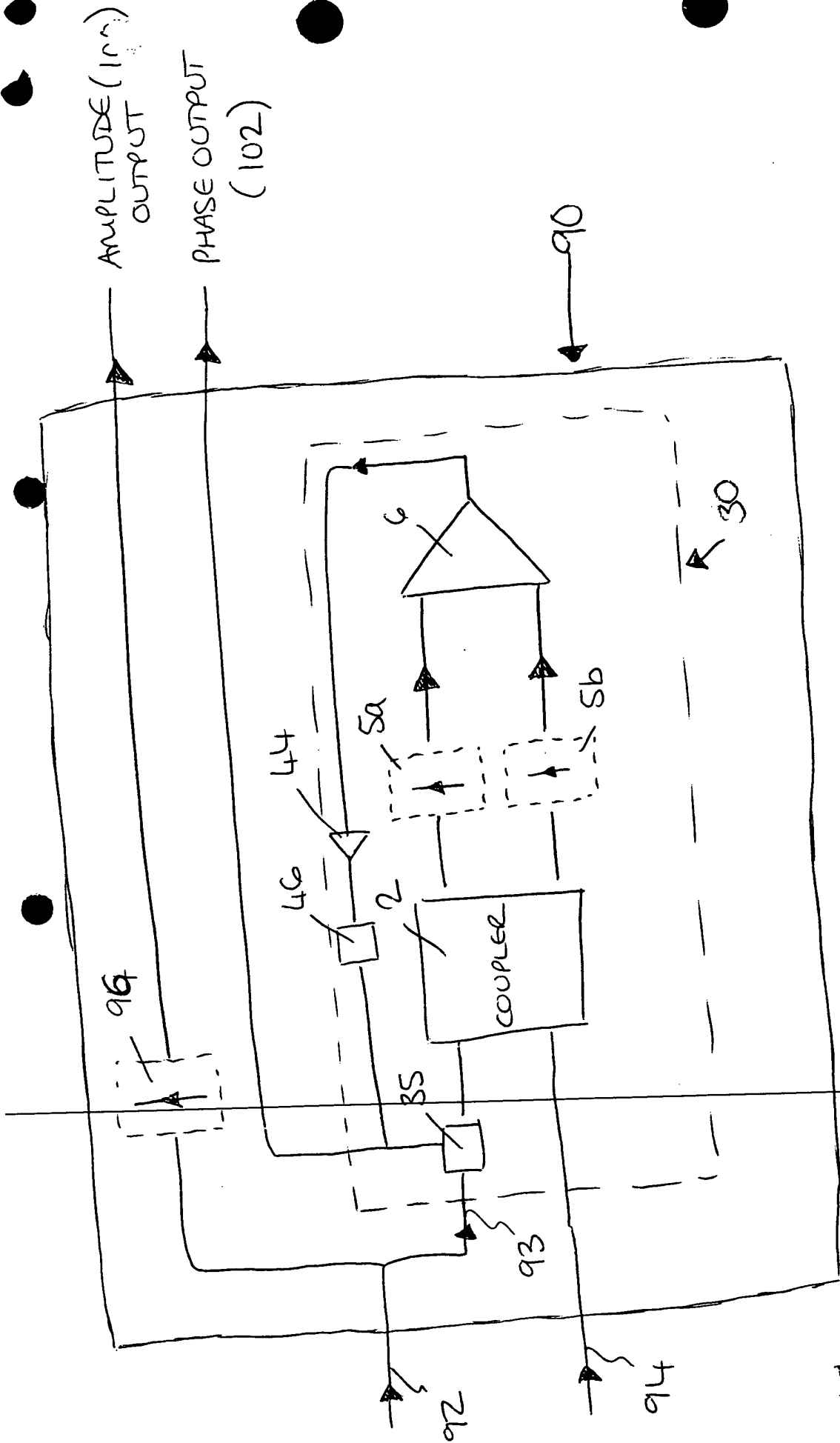


FIGURE 14

NOT TO BE AMENDED

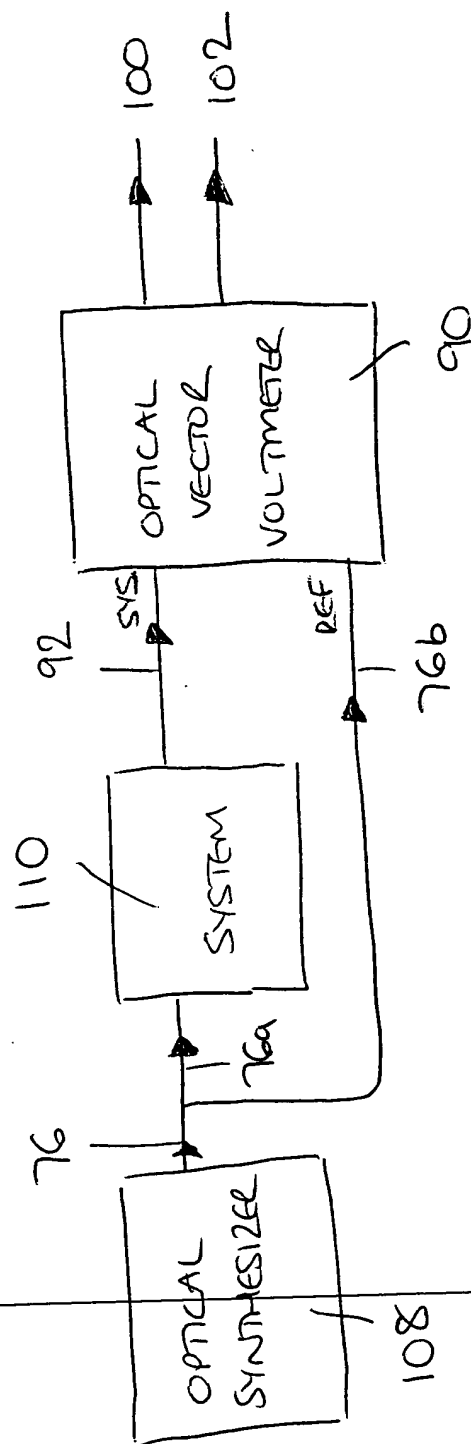
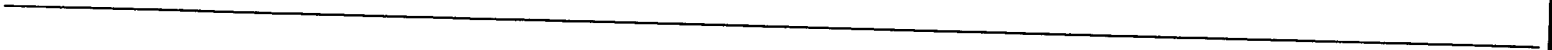


FIGURE 15



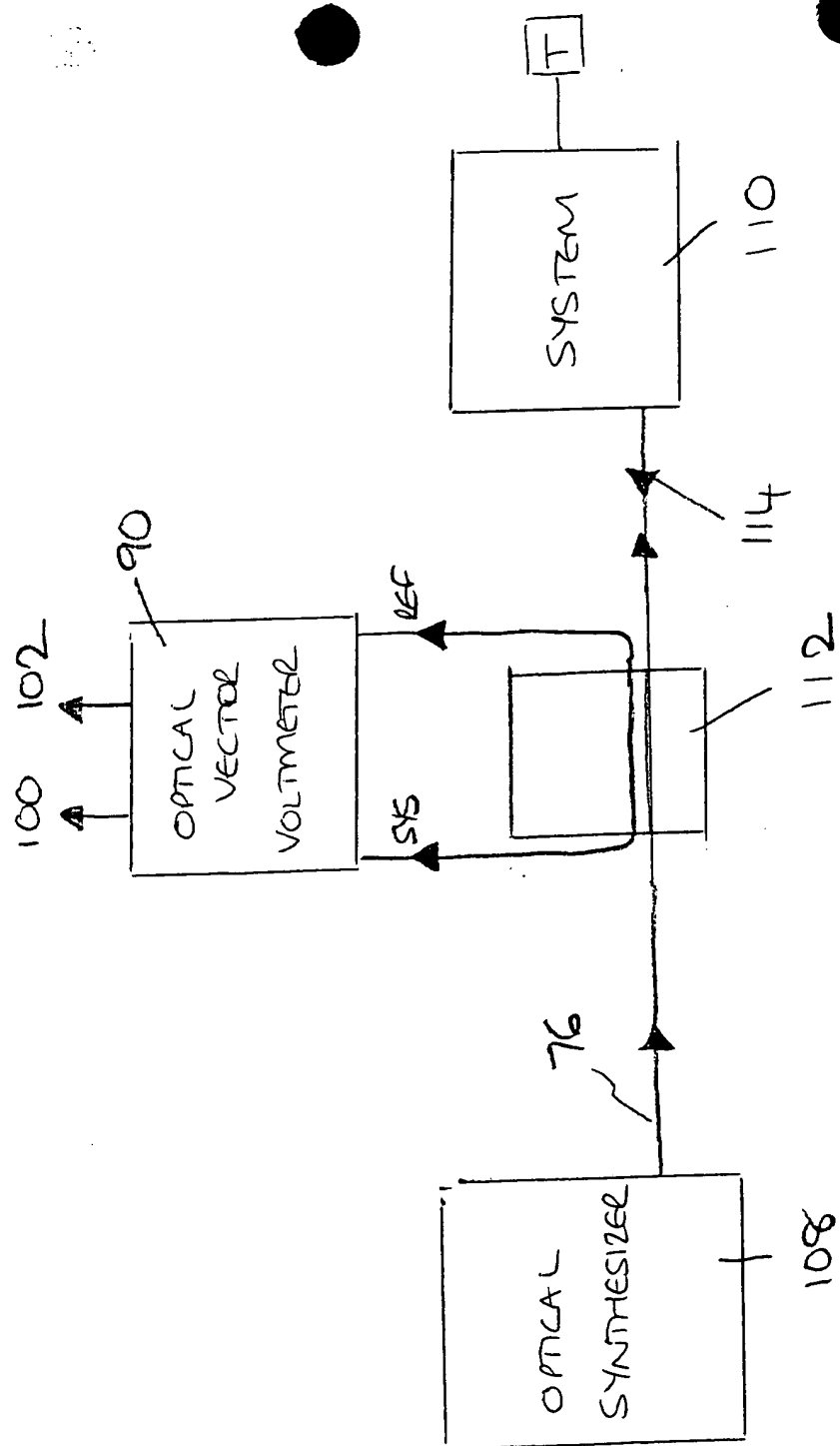
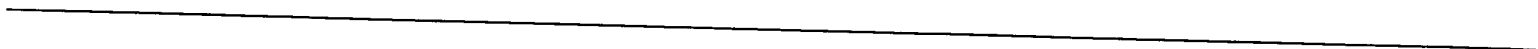


FIGURE 1G



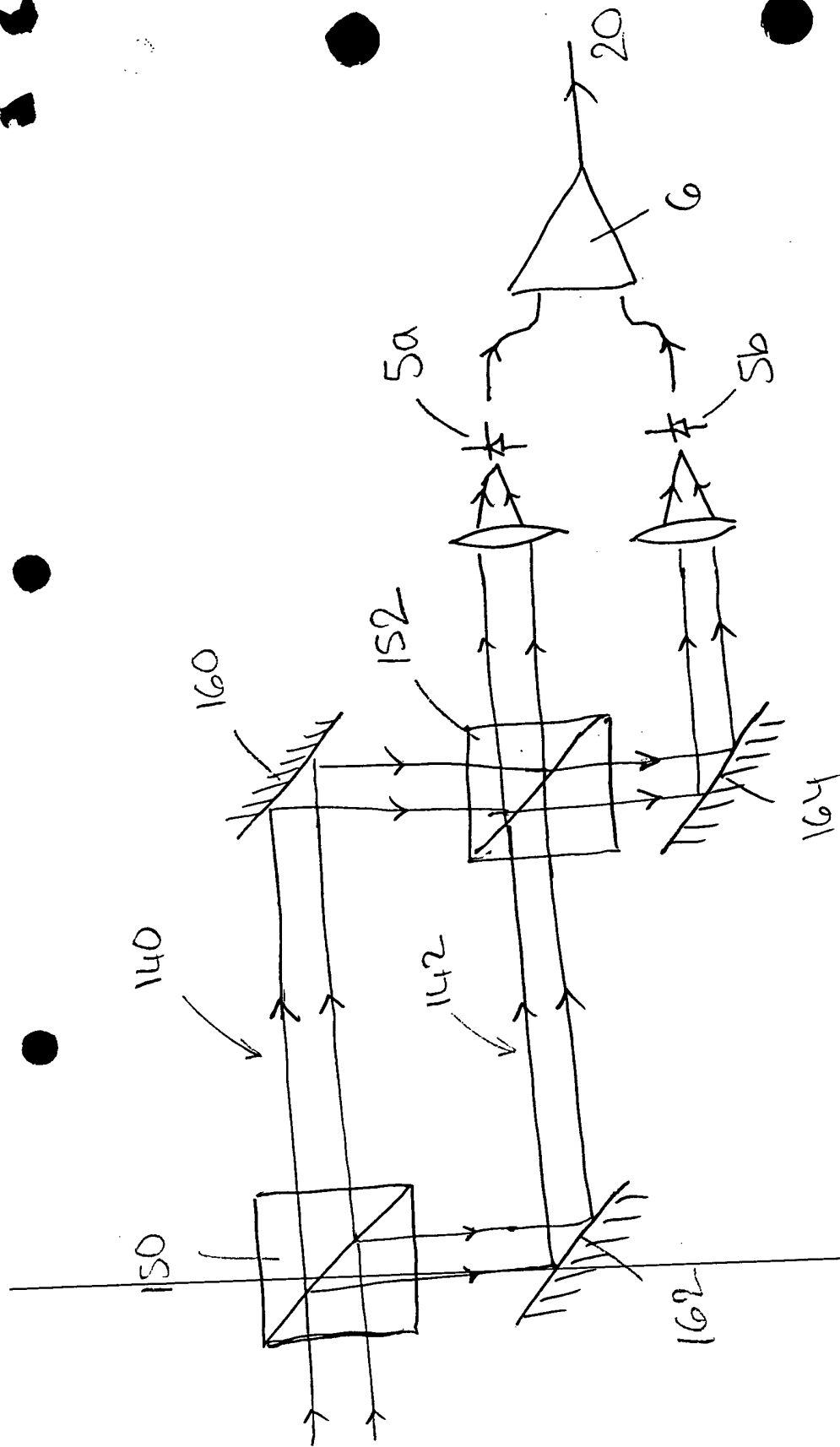


FIGURE 17

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22.9.99
